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ITS for Connected Mobility

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Contents

Preface

The International Scientific Conference on Mobility and Transport, “mobil.TUM” was introduced in 2008 by the Institute of Transportation at Technische Universität München. Since then, the conference was held with a focus on various topics, with the intention to develop and foster a regular scientific, international and interdisciplinary forum for dialogue – within a dynamic world of mobility and transport.

mobil.TUM 2013 was organized by the Chair of Traffic Engineering and Control under the heading “ITS for Connected Mobility”. Intelligent Transport Systems and Services (ITS) provide a wide variety of solutions to existing transport problems and to the ecological and societal challenges presented by an increasing demand for mobility. With growing capabilities of information and communication techniques, the participants of the mobility system are becoming increasingly connected. A future with high fidelity transport information in a seamlessly connected mobile world for all types of traveler draws ever nearer. In order to respond to the multifaceted character of these developments, science and practice within the mobility domain involve an increasingly broad range of different disciplines.

The conference focused on various aspects of increasing connectivity within intelligent transport systems. Topics of interest included,

- interactions between personalized ITS-technology and the individual as well as the society
- traveler’s behavior in a connected transportation system, influence of assistance systems
- designing and modeling mobility in a multi-modal environment
- progress in traffic flow theory and modeling of cooperative transport
- new technologies for data collection, data fusion, consistency and quality of information
- cloud computing, internet of things and related theories applied to cooperative ITS
- cooperative traffic control at hotspots, in networks and at special events
- progress in transport system simulation on various scales
- increased automation and self-organization in traffic, competition with public strategies

The conference was organized in paper sessions, poster sessions and panel discussions with the five main topics *Modelling and Simulation; Multi-modal Cooperation and Interaction; Technologies, Applications and Solutions; Field Operational Tests* and *Generic Concepts and Visions.*

A total of 33 papers had been selected in a two-step peer review process for presentation at the conference. The scientific advisory board consisted of the renowned international experts Michael G.H. Bell (Sydney, Australia), Robert Bertini (Portland, USA), Michel Bierlaire (Lausanne, Switzerland), Martin Fellendorf (Graz, Austria), Larry Head (Tucson, United States), Ben Heydecker (London, Great Britain), Serge Hoogendoorn (Delft, Netherlands), Matthew G. Karlaftis (Athens, Greece), Haris Koutsopoulos (Stockholm, Sweden), Jean-Baptiste Lesort (Lyon, France), Huapu Lu (Beijing, China), Vito Mauro (Turin, Italy), Hideki Nakamura (Nagoya, Japan) and Yiik Diew Wong (Singapore).

In a subsequent peer review process following the conference, 14 papers were selected for publication within this book.

We would like to thank the authors for their rich contributions to the conference and especially to the book at hand.

The conference has been an exciting opportunity to meet and exchange ideas. A great deal of inspiration has emerged from the presentations, discussions and informal networking. May this book capture and reflect these ideas, so that we can build upon them individually and as a community.

Fritz Busch, Matthias Spangler

October 2014

ITS for Connected Mobility

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Abstract

The transportation system is the backbone of the United States' economy, and transportation is an essential part of everyday life for American citizens. It is essential that the transportation system continue to provide accessibility and connectivity to an ever-evolving global economy. A key way to do so is to embrace, develop and implement new technologies. One of the newest and most promising facets of transportation-related technology is in the field of connected mobility. The vision behind connected mobility is of a transportation system where vehicles, travelers, and infrastructure are all wirelessly connected with one another and able to transmit real-time data about things like weather, location, and vehicle and infrastructure status. Such a degree of connectivity could have substantial benefits for the safety, mobility, and sustainability of the domestic transportation system, including accident prevention and congestion reduction. In recent years, major strides have been made into the research and development of connected mobility technology and some field-testing has commenced, but there is a need for more attention and investment from stakeholders throughout the transportation community and beyond.

1. U.S. Transportation Sector Priorities and Impacts

1.1 Introduction

The transportation network is the backbone of the United States' economy. Without an adequate and effective transportation system, our nation would be incapable of functioning efficiently and effectively. Transportation for people and goods is an essential aspect of almost everything people do in their daily lives, from commuting to work to visiting friends and family to going to school, accessing health care and going out for a meal; thus the domestic transportation network needs to be able to provide every American with the ability to get where they need to go safely, efficiently and sustainably. In this ever-changing world, that is not a simple task and requires constant evolution and innovation among U.S. transportation agencies at the local, state and federal levels as well as in the private sector. Over the past few decades, the field of intelligent transportation systems (IST) has grown substantially and contributed significantly to improvements in transportation systems operations throughout the world. One of the most recent developments in ITS is the concept of connected mobility, which has the potential to greatly improve the safety, efficiency, and sustainability of the U.S. transportation system, and is deserving of more attention from the transportation community so that it can be more thoroughly understood and eventually implemented throughout the nation.

1.2 Transportation Priorities

Former U.S. Secretary of Transportation Ray LaHood and current U.S. Secretary of Transportation Anthony Foxx have designated a number of priorities for the nation's transportation system that should be focused on moving forward. Given how much time is spent in the transportation network by a typical American, it is not surprising that safety is one of the main priorities identified by both LaHood and Foxx. Improving public health and reducing the prevalence of transportation-related injuries and fatalities are two specific safety-related priorities that LaHood has identified. Other priority areas that LaHood laid out during his time as Secretary of Transportation include keeping domestic infrastructure in a state of good repair, using transportation to bring about lasting and equitable economic benefits throughout the country, promoting more liveable communities through transportation policies and investments that increase accessibility and transportation choices, and focusing on reducing harmful emissions and externalities from transportation sources. Secretary Foxx, who was sworn in to the post only a few months ago, was broader in naming his priorities. In addition to safety, Secretary Foxx has called for improved efficiency and productivity through better use of technology, data, and innovation, investing in a multimodal transportation system and new transportation technologies, and making use of policies that will promote improve sustainability, quality of life, and opportunity. Many of the priorities stated by both former Secretary LaHood and current Secretary Foxx could be addressed by placing more focus upon connected mobility.

1.3 Transportation Impacts

The U.S. transportation sector has enormous impacts on nearly every aspect of American life, including safety, the economy, mobility, and sustainability. In 2010, there were 32,788 fatalities on the transportation network. While this represents a 3% decline from 2009, it is still a large and disturbing number that should raise major questions about what can be done to improve the safety of the transportation network. For Americans between the ages of 4 and 34, transportation-related fatalities are actually the leading cause of death, meaning that the transportation network is robbing the nation at an alarming rate of young and bright minds that do not get their chance to contribute to society. Aside from the sheer number of fatalities on the transportation network, in 2009 there were also 2.2 million injuries and 5.5 million total crashes which racked up a total cost of $230 billion, a massive expense that has all kinds of ramifications for the economy. Another negative impact that the transportation network is currently having on the economy comes in the form of traffic congestion and lost work time. Annually, Americans spend nearly 5 billion hours sitting in traffic, and the cost of all that congestion to the nation is about $115 billion. In addition to safety and economic impacts, the transportation sector also has significant environmental externalities. The transportation sector is responsible for 28% of the nation's greenhouse gas emissions, 29% of its energy consumption, and 70% of its petroleum consumption. As a result of all of this pollution and energy consumption, half of all Americans live in areas that exceed air quality standards for at least one pollutant.

2. ITS in the United States

2.1 Evolution of ITS Program

Table 2.1 shows the evolution of the nation's ITS program over time. The first official legislation adopted that was related to ITS was ISTEA in 1991. Since ITS was a newly emerging field at that point, funded activities were primarily concerned with research and development and the creation of standards. Lessons learned included the fact that agencies and industry needed to work together in different ways. Following ISTEA was TEA-21, passed in 1998. With proven technologies and solutions under ISTEA, TEA-21 departed from research and emphasized the need to overcome challenges and barriers facing the deployment of ITS and created the ITS Deployment Program. In 2005, SAFETEA-LU marked a return to research and development and provided for the mainstreaming of ITS technologies. The ITS Strategic Plan launched in 2009 is the basis upon which the current research and development initiatives are operating. The latest piece of legislation, MAP-21, passed in 2012, is the bill currently in place to provide continued funding for ITS research in the connected mobility arena.

Congressional Legislation	Dates and Mission
Intermodal Surface Transportation Efficiency Act (**ISTEA**)	1991–1997 (extended to July 1998) ▪ Research and Development ▪ Operational Tests ▪ Technical assistance including architecture and standards
Transportation Equity Act for the 21st Century (**TEA-21**)	1998–2003 (extended to August 2005) ▪ Policy and Institutional Challenges to Deployment ▪ ITS Deployment Program (Congressionally designated) ▪ Model Deployment Initiatives
Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (**SAFETEA-LU**)	2005–2009 (extended to March 31, 2012) ▪ Research ▪ Mainstreaming ITS
Moving Ahead for Progress in the 21st Century (**MAP-21)**	2012-2014

Table 2.1: Evolution of ITS Program

2.2 ITS Deployed Technologies and Numbers

Since the passage of ISTEA in 1991, the United States has made use of many different ITS technologies in its transportation network. Some of the most commonly deployed technologies throughout the nation are closed-circuit television cameras, which can be used for a number of different transportation-related purposes, electronic toll payment, traffic measurement sensors and loops, and dynamic message signs which are used to display information about travel times, delays, construction, Amber Alerts and other information of importance to travelers.

Along with technological improvements to the transportation infrastructure have come significant gains in intelligent vehicle technology. In 1990, a standard Honda Accord might have been considered an state of the art vehicle. The major attributes which led to this designation were the inclusion of automatic shoulder belts and a CD player, and the car lacked both ABS and air bags. The Accord got an EPA-estimated 22 miles per gallon. Fast-forward 23 years, and its clear how far vehicles have come. A 2014 Ford Focus is an "intelligent vehicle" and has everything a 1990 Honda Accord had, plus air bags, ABS (now standard in most vehicles), stability control and a wide array of other “intelligent“ features. These include rear-view cameras, active parking assistance, forward collision warnings, and a Blind Spot Information System. The point is that intelligent vehicles are here and available on the market.

A look at some of the numbers relating to ITS deployment in the United States shows just how prevalent it has become in the transportation system. The market for ITS products and services in a massive $48 billion industry, and ITS programs have received a combined $21 billion in funding from federal and municipal sources. More than 75% of the fixed route bus agencies in the nation make use of automatic vehicle location services. 40 states use commercial vehicle electronic screening technology at 360 weigh stations. Finally, 54% of freeways and 50% of intersections in the 75 largest metro areas in the United States are under automated surveillance.

3. Current and Future Innovations in ITS

3.1 Vision for a Connected Future

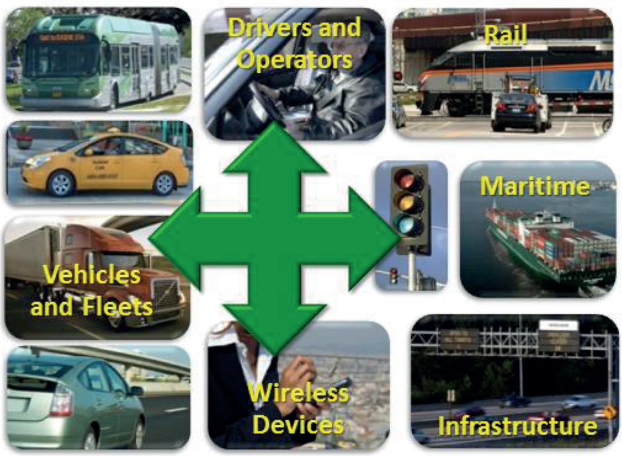

Figure 3.1: Connected Mobility Vision

The development and deployment of ITS technologies in the United States has come a long way over the past several decades, but new and exciting technologies are still being established and studied today that could help to significantly negate some of the negative impacts that the transportation system is currently having on the safety, economy, and sustainability of the nation. Perhaps the most substantial and promising recent development in ITS is the idea of connected mobility and vehicles that can automatically communicate with one another. In the past, the transportation community has primarily focused on how to connect vehicles with infrastructure, but as shown in Figure 3.1, connected mobility takes that idea much further.

The core concept behind connected mobility is of a multimodal surface transportation system where every component of the system, including all vehicles, drivers, operators, mobile devices and the infrastructure, are connected to one another. The goal is that technology can be leveraged in such a way that through the use of wireless communications, safety, mobility, and sustainability of all modes in the transportation system can be maximized. This includes private automobiles and fleet vehicles of all kinds (public transportation, commercial vehicles, taxis, car-sharing, government and private fleets, etc.). This connectivity can be provided through factory-installed equipment as well as by incorporating after market devices.

Of these three focus areas, safety is the top priority, and connected mobility has the potential to help prevent a majority of typical crash scenarios. Figure 3.2 below depicts the scenarios behind 80% of crashes on U.S. roadways. The image on the right side of the figure shows the types of information that could be relayed between vehicles if they were fitted with communication devices. By being able to communicate data such as location, speed, and braking status, the typical crash scenarios shown in the figure could be prevented, significantly improving the safety of the transportation system.

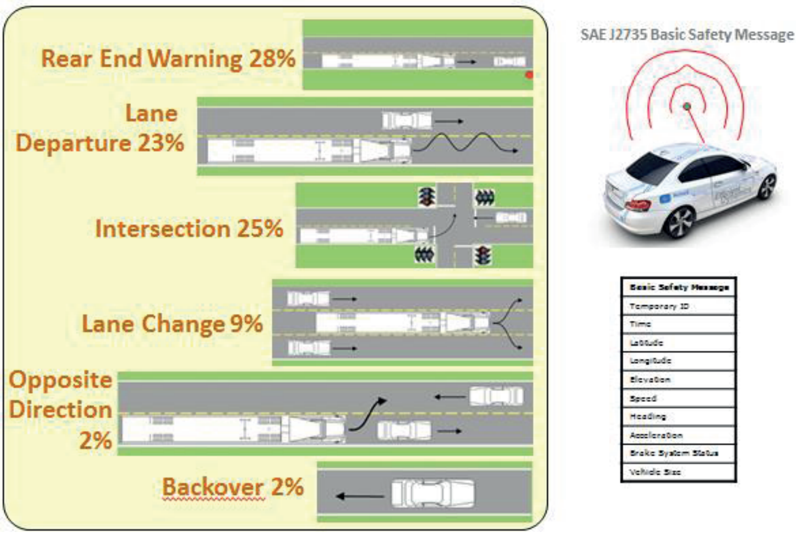

Figure 3.2: Typical Crash Scenarios and Basic Connected Vehicle Safety Message

3.2 Connected Vehicle Safety Pilot Program

In order to gain some insight into the effectiveness of connected vehicle technology and the possible benefits that could be gathered from it, as well as to determine how these technologies would be accepted by actual drivers, in 2011 the Department of Transportation developed the Connected Vehicle Safety Pilot Program, a large-scale field test in which existing connected vehicle technologies such as forward collision warnings and pedestrian detections were implemented into the real world. Several different types of vehicles, including cars, trucks, and buses (also at least one motorcycle and one bicycle), were outfitted with available technologies and deployed for one year in Ann Arbor, Michigan, and numerous types of data were collected. Table 3.1 contains a summary of the vehicles used and the technologies used in them, and Figure 3.3 shows a site plan for the Ann Arbor deployment.

Connected Vehicle Device	Vehicle Type	Vehicle Source	Total Units in Model Deployment
Integrated Devices	Light Vehicles	CAMP	64
Integrated Devices	Commercial Trucks	Battelle Team	3
Vehicle Awareness Devices	Light Vehicles	UM, Ann Arbor	2200
Vehicle Awareness Devices	Local Truck Fleets	Con-Way, Arbor Springs	50
Vehicle Awareness Devices	Heavy Duty	University Fleet	100
Vehicle Awareness Devices	Transit Vehicles	AATA	100
Aftermarket Safety Devices	Light Vehicles	UM, Ann Arbor	300
Retrofit Devices	Local Truck Fleets	Con-Way, Sysco	16
Retrofit Devices	Transit Vehicles	UM Buses	3
		Total	**2836**

Table 3.1: Safety Pilot Deployed Vehicles

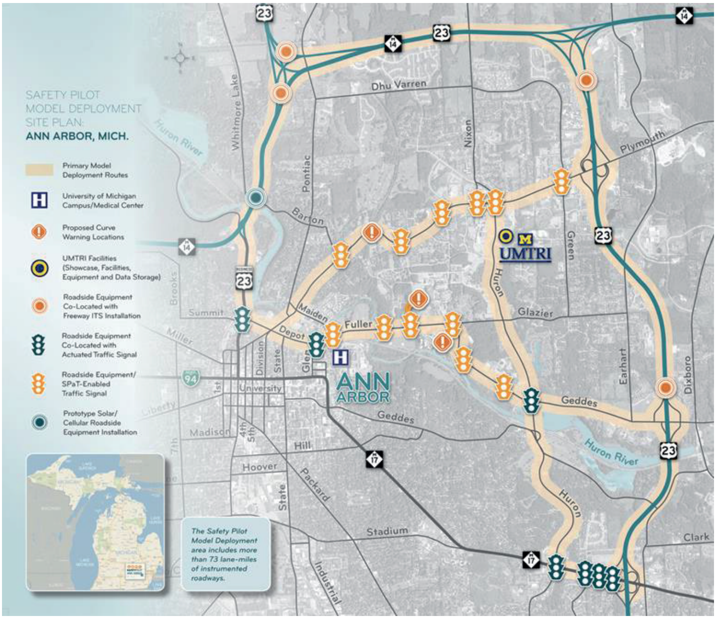

Figure 3.3: Safety Pilot Deployment Site Plan

4. Connected Mobility Programs and Testing

4.1 Mobility Programs and Applications

The continued emergence of connected mobility technology will lead to new and large sources of valuable data that can be collected and analyzed by the transportation community. Figure 4.1 demonstrates some of the potential data sources from connected vehicles, mobile devices, and infrastructure, such as weather data and location data, that can be made available using connected vehicle technology and be input into a broad and informative data environment. The vision for the future is that of all of these data will be integrated together for use in transportation management, traveler information and multimodal performance measurement. This fusion of large amounts of data from multiple sources would reduce costs of data management and eliminate many of the barriers that currently exist to the capture, management, and sharing of data.

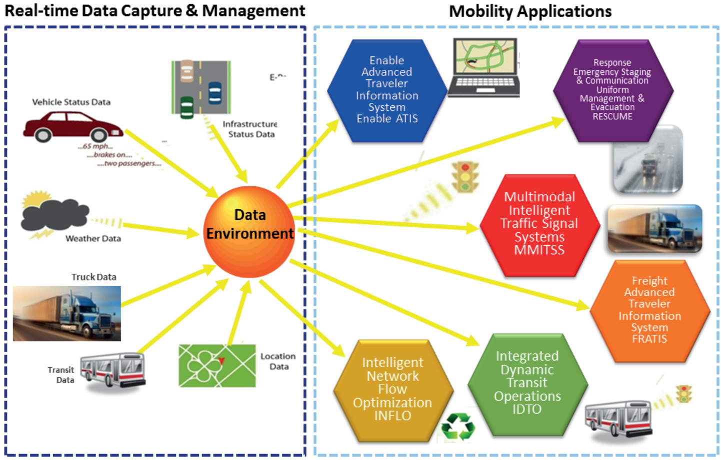

Figure 4.1: Mobility Program

With all of these data, the potential exists to create a transportation version of the App Store. A vast array of applications could be developed using frequently collected and disseminated data from connected vehicles, travelers, and infrastructure and used in many different ways to improve the transportation system. Once such applications begin to be developed, it will be necessary to assess each one's to improve the nature, accuracy, speed, and precision of dynamic decision making by the users. The most promising applications would be those that demonstrate the ability to significantly improve the transportation system's capability to provide safe, secure, and reliable movement of goods and people. Over the past few years, many promising dynamic mobility applications, six of which are identified in Figure 4.1, have been developed. In addition to these, the DOT's AERIS program has led to the development of several applications designed to support and facilitate sustainable transportation choices.

4.2 Test Bed Investments

With these new connected mobility technologies, transportation data sources and applications comes the need for further field trials and testing. In order to encourage and support connected vehicle testing, the DOT has a Connected Vehicle Test Bed program, in which seven locations across the country have been designated as sites for members of both the public and

Figure 4.2: Test Bed Investments

private sectors of the transportation community to partake in research and testing of connected mobility technology. Figure 4.2 shows the location of each designated test bed. The work done at each of these test beds should provide both federal and state officials, as well as private sector partners with a valuable foundation for the eventual deployment of connected vehicles across the nation.

5. Objectives, Issues, and a Call to Action

5.1 Objectives and Issues

The ultimate objective of continued research and development of connected mobility technology is to lead to improvements in the three main priority areas of the transportation system, safety, mobility, and sustainability. While safety may be the top priority of the three, as shown in Figure 5.1, it is perhaps best to combine the desired objectives from each area together, because many of the problems in each area are related to one another and advancements in connected mobility will lead to significant benefits for all three. We need to understand how these three objectives are related to one another in terms of trade-offs. The vast array of potential benefits to be realized from an enhanced focus on connected mobility means that there are a lot of stakeholders when it comes to this technology. They include the general public, vehicle manufacturers, public agencies, private companies, special interest groups, and academia, and this diverse group will need to coordinate and cooperate to make sure that benefits from connected mobility are maximized.

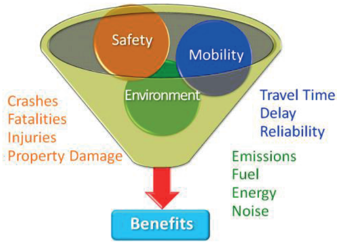

Figure 5.1: Combined Objectives

There is also a need to focus on international partnerships, particularly in the development of the necessary standards for connected mobility. There has been progress through cooperation between the U.S., Europe and Japan. Of course, with so many stakeholders comes a range of policy issues that must be addressed and overcome. As is depicted in Figure 5.2, each of these issues, such as liability, financing, and sustainability, can be seen as individual puzzle pieces, and it will be up to the stakeholders and leaders in the transportation community to work collaboratively to determine how they all fit together to form a clear vision of connected mobility for the future.

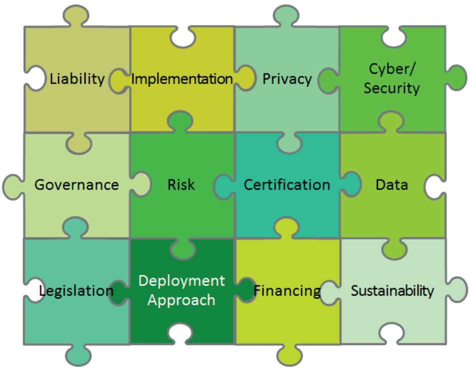

Figure 5.2: Policy Issues

5.2 Research Call to Action

There can be no disputing that the field of connected mobility is incredibly promising for the future of the transportation system in the U.S. and across the globe. Through comprehensive research and development, and smart implementation, connected mobility technology has the potential to bring about significant improvements to many of the negative aspects of the current multimodal transportation system, particularly in the areas of safety, mobility, and the environment. This potential is why it is imperative that greater effort be placed into researching connected mobility in the United States and abroad. Data from demonstrations and field tests need to be archived and shared with all relevant parties, and the tests themselves should become cooperative endeavors between the private and public sectors. The U.S. DOT, which has been behind the majority of domestic connected mobility research, should reach out to the NSF, DOE, and DOD and promote collaboration. Future research should focus on topics like possible distractions caused by connected mobility technology, implementers of the technology, and infrastructure requirements. In addition, all research should be policy-relevant, and the transportation community should take advantage of its authority to shape policies that can embrace connected mobility. The future of this field is very bright, but getting there will require a lot of effort from everyone in the transportation community.

References and Resources

1. U.S. Department of Transportation Strategic Plan 2012-2016.
2. U.S. Department of Transportation Intelligent Transportation Systems Strategic Research Plan, 2010-2014, Transforming Transportation Through Connectivity.
3. National Highway Transportation Safety Administration Connected Vehicles.
4. Safety Pilot Model Deployment.

Abbreviations

ITS	Intelligent Transportation Systems
ISTEA	Intermodal Surface Transportation Efficiency Act
TEA-21	Transportation Efficiency Act for the 21st Century
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users
MAP-21	Moving Ahead for Progress in the 21st Century
ABS	Antilock Braking System
DOT	Department of Transportation
AERIS	Applications for the Environment: Real-Time Information Synthesis
NSF	National Science Foundation
DOE	Department of Education
DOD	Department of Defense

Part I: Modeling and Simulation

Robust Signal Timing Optimization vs. Adaptive Control on High Volume Arterials

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Abstract

Signal timing plans are routinely challenged by varying demands and capacities. Coordinated traffic actuated, traffic responsive, and adaptive signal control systems are all attempts to address this problem by increasing the intelligence of traffic signal control hardware and software. While adaptive signal control systems may eliminate the need for the development of signal timing plans, they are complex, and require extensive and expensive surveillance systems.

The objective of the study is to develop an optimization procedure for developing signal timing plans that must perform satisfactorily under a wide range of traffic demand and capacity conditions. The study also aims to evaluate the performance of the proposed optimization method against traffic responsive and adaptive signal control. We developed a robust optimization algorithm based on a weighted combination of the traffic demands and capacities on each intersection approach over the course of the day, as opposed to the conventional approaches of timing plans optimized for the peak period or average volumes.

The signal settings from the proposed optimization method have been evaluated on a ten-intersection signalized arterial, which is part of the Pacific Coast Highway in Los Angeles, CA. The arterial carries heavy traffic volumes and experiences congestion with long queues for most of the peak periods. The study corridor is part of the Los Angeles Automated Traffic Surveillance and Control (ATSAC) system and runs under adaptive control. The proposed robust optimization method has shown through numerical examples that it can effectively address the variations in traffic demands and has similar performance compared to time of day and adaptive signal control. Adaptive signal control is mostly effective under non-recurrent incident conditions where it can respond to changes in capacity.

Introduction

Optimal signal control settings are critical for ensuring efficient traffic operations in high volume signalized arterials. The time-varying character of demand and capacity characteristics in such urban networks dictate that several signal timing plans are developed to match the prevailing traffic patterns throughout the day. Traffic engineers have typically approached this issue by designing traffic signal timing plans for different times of day. However, these time of day plans are often suboptimal because they are based on average values of demand under constant capacity and are not responsive to unpredictable changes in demand or capacity, e.g., due to incidents. Especially for intersections with high variability in demand or capacity, suboptimal signal timing plans can result to oversaturated conditions causing long queues and extensive delays. Coordinated traffic actuated, traffic responsive and adaptive signal control systems have attempted to address the problem that demand and capacity variability causes by responding to such changes in real time. However, these systems are often complex to operate and require expensive surveillance and communication systems. There is a clear need to develop robust traffic signal timing plans that while suboptimal for each time period individually, they can ensure acceptable performance under a wide range of demands and capacities.

The literature has several examples of methods for developing robust signal timing plans. The majority of the studies have been based on developing signal timings for various demand scenarios and designing methodologies and optimization procedures to choose among the different plans. Such research efforts first develop sets of demand scenarios and in some cases saturation flows and design robust signal timings by minimizing a specific metric, for example, delay, or a weighted combination of mean delay per vehicle and the standard deviation of delay [1, 6, 11, 12]. The TRANSYT-7F model documentation suggests developing optimized signal settings for different periods within a day and using the model to evaluate their performance over the whole day in order to select a single plan to be implemented [9].

Finally, several studies have focused on determining the level of demand to be utilized for signal timing optimization. Average hourly volumes have been used in the past [5], even though this approach often leads to oversaturated conditions. Heydecker [6] states that the use of average values is appropriate only when there is small variability in the available data set. Skabardonis [7] has suggested that in order to determine a single timing plan that is robust and avoid oversaturation of certain high volume approaches, one should first determine the minimum cycle length and splits that do not oversaturate any movements and then calculate offsets that provide progression for the average volumes throughout the day. Other researchers have suggested utilization of different percentiles (e.g., 90^{th} or 95^{th}) of volumes or volume to capacity ratios as inputs in commercial software that are then used to optimize the signal settings [4, 8].

Despite the plethora of existing studies, only a couple of them have focused their efforts on developing plans that are robust to changes both in demand and capacity. An early study by Heydecker [6] considered variation in demand and capacity but it was focused on a single intersection. A more recent study by Dowling et al. [4] attempted to develop signal timing plans for signalized arterials accounting for the variability in both demand and capacity. In particular, they designed a single timing plan based on the 95% cumulative percentile of the flow ratios for the critical movement of the whole arterial. However, the study assumed that the observed flow ratios for the critical movement can be described by a normal distribution, which is not always the case. There is a need to develop a method for designing a single robust single timing plan that recognizes that demand and capacity changes occur during the day due to the time-dependent character of travel demand and the existence of capacity restriction situations.

This paper presents a method to design robust signal control settings for high volume signalized arterials. This method utilizes demands and capacities that are weighted averages of demand volumes and saturation flows observed over the course of the day. The cycle length is optimized based on the intersection that presents the highest weighted flow ratio to avoid oversaturated conditions, while the offsets and splits are optimized using the commercial software Synchro [10].

The rest of the paper is organized as follows. First, we present the method for calculating the average demands and capacities to be used in the development of the signal timings. Then, we describe the study site used to evaluate the proposed method. The following section presents a comparison of the designed robust signal timing plan with the existing adaptive and the developed time of day signal timing plans for varying demands and one scenario of varying capacities. The final section summarizes the study findings and discusses areas that future work should focus on.

Research Approach

The proposed method aims to determine the cycle length, offsets, and splits that will allow a signalized arterial to operate effectively during the whole day utilizing only one set of signal settings. This is achieved by calculating the weighted averages of demand volumes and capacities (saturation flows) and consequently weighted intersection flow ratios that are used to optimize the signal settings. This approach is expected to lead to signal settings that can achieve efficient traffic operations and therefore are robust for the whole day. In order to explain the method for calculating the weighted averages of the demands and saturation flows, let us assume that signal timings are designed for 12 hours of traffic operations and the demands and saturation flows change every 3 hours. Denote the demands and saturation flows for a time period *t* and lane group *j* by $v_{j,t}$ and $s_{j,t}$ respectively. Then, the weighted average of the demands for that lane group can be calculated as follows:

$$\overline{v_j} = \frac{1}{4}v_{j,1} + \frac{1}{4}v_{j,2} + \frac{1}{4}v_{j,3} + \frac{1}{4}v_{j,4} \quad (1)$$

and the weighted average of the saturation flows as follows:

$$\overline{s_j} = \frac{1}{4}s_{j,1} + \frac{1}{4}s_{j,2} + \frac{1}{4}s_{j,3} + \frac{1}{4}s_{j,4}. \quad (2)$$

Since the focus of this study is on high volume arterials, the signal cycle, which is assumed to be common for all intersections on the arterial of interest, is optimized based on the intersection with the highest weighted flow ratio during the day. The intersection with the highest weighted intersection flow ratio is chosen to determine the system cycle length because it ensures that on average oversaturated traffic conditions will be avoided. The optimal signal cycle, C_o, can be calculated as follows [2]:

$$C_o = \frac{L}{1 - \sum_{j=1}^{J} y_j} \tag{3}$$

where L is the lost time for the subject intersection, y_j is the weighted flow ratio for lane group j and J is the total number of lane groups for the subject intersection. This value is the minimum cycle length that ensures undersaturated conditions for all intersections. Longer cycle lengths may improve the performance at the critical intersection at the expense of higher delay for the rest of the intersections in the system.

Next, the optimized signal cycle that is calculated by equation (3) as well as the weighted averages of demands and saturation flows throughout the day are used as input to Synchro. Synchro optimizes signal offsets and splits by minimizing a combination of delay and stops for the whole arterial under consideration.

Study Site

The study site used to evaluate the performance of the proposed signal timings consists of a ten-intersection signalized arterial, which is part of the Pacific Coast Highway (PCH) in Los Angeles, CA. The test arterial segment runs from the intersection of the PCH with the Topanga Canyon Boulevard to the intersection with California Incline in the south-eastbound direction, a total distance of about 7 miles (see Figure 1). This is a very congested segment that experiences long queues during most of the peak hours. This arterial segment is characterized by high variability in its demand volumes over the day. A coefficient of variation for the hourly volumes of 15-33% is observed for the eastbound direction and 7-23% for the westbound direction. The traffic signals operate under the Automated Traffic Surveillance and Control (ATSAC) adaptive signal control developed by the Los Angeles Department of Transportation [3]. The ATSAC system provides real-time data on cycle-by-cycle signal settings and traffic demands that allow for a comprehensive comparison of the proposed robust signal timing optimization with the adaptive control for a variety of demand and capacity scenarios. Figure 2 shows the system cycle length over the day at the intersection of PCH with the Topanga Canyon Boulevard. The arterial runs under adaptive control from approximately 7am to 7pm, and the rest of the time the signals operate as isolated fully actuated.

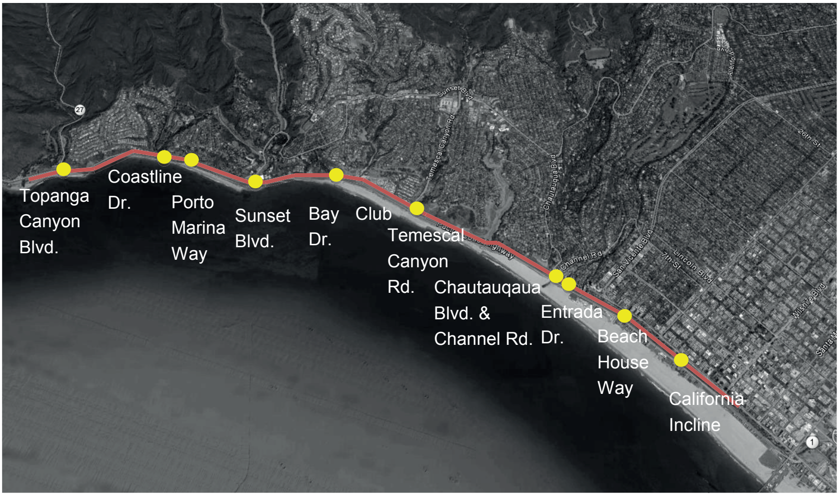

Figure 1: Ten-intersection study site of Pacific Coast Highway (source: Google Earth).

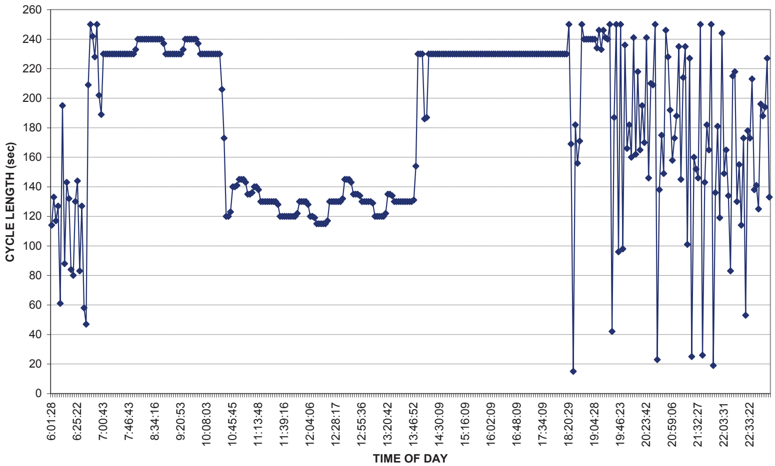

Figure 2: Cycle length vs. time of day—Intersection of PCH and Topanga Canyon Blvd.

We focused on developing robust timing plans during the adaptive signal system operation (12 hours, 7am-7pm) and specifically the following time periods:

- Morning (AM) Peak: 7-10am
- Midday: 10am-2pm
- Afternoon (PM) Peak: 2pm-7pm

In addition, we have developed time of day plans for each of these time intervals based on the respective average hourly volumes with the use of Synchro.

Results

The intersection of PCH with the Chautauqaua Boulevard and Channel Road was found to be the one with the highest weighted intersection flow ratio, calculated by using the weighted average values of demand and saturation flows for the time period of interest. Therefore, the weighted intersection flow ratio for that specific intersection was used to determine the cycle length in order to ensure that on average none of the intersections will be experiencing oversaturated traffic conditions. This weighted intersection flow ratio was calculated to be $Y = 0.92$, which resulted in an optimal cycle length of C_o =197 sec, based on equation (3). The cycle length used to further optimize signal offsets and splits was rounded up to 200 sec.

Note that the approach to select the cycle length based on the highest weighted intersection flow ratio does not guarantee that oversaturated conditions will be avoided for all movements (lane groups) in the network at all times. However, as we will see next, even though some of the movements become oversaturated, this does not always affect the overall performance of the arterial, which performs similarly and in some cases better compared to the time of day and adaptive signal settings.

Demand Variability

The robust signal timing plan proposed for the 12-hour period for the ten-intersection arterial segment of the PCH is compared against the existing adaptive signal timing plan and the time of day signal timing plan that was developed for each of the three time periods of interest, i.e., AM peak, PM peak, and midday. In the following sections, we discuss in detail the results from the AM and PM peak periods, since they were the most critical in determining the effectiveness of the proposed method.

The total system-wide delays and stops for all three timing options and scenarios tested as obtained from Synchro are reported in Table 1. A comparison of the three timing plans for the AM peak indicates that the proposed signal timing plan outperforms the adaptive one. Figure 1 illustrates that for the majority of the intersections the proposed signal timing plan performs similar to the time of day and adaptive ones with respect to the average delay per vehicle and the average number of stops.

The robust signal timing plan results in higher average delays for the intersection of PCH with the Topanga Canyon Boulevard by 23% compared to the adaptive plan, because the green time under the robust plan is not sufficient to serve the high volume of the left movement on the Topanga Canyon Boulevard turning on to PCH. The green time was optimized for the weighted average volume for this movement which is much lower than the

AM peak demand volume. This is a result of the very high variability among the three time periods (coefficient of variation is more than 50%).

Another interesting observation is that for Bay Club Drive the robust timing plan results to higher average delay than the other two timing plans but lower number of stops, indicating that the proposed signal timings often lead to vehicles being stopped fewer times but having to wait longer.

The performance of the proposed signal timing plan for the midday appears to be similar to that of the AM peak, with the difference that both the total delay and the total number of stops are slightly higher compared to the adaptive signal timing plan. However, for individual intersections, the differences in average delay and average number of stops between robust and adaptive signal timing plans are very small.

For the PM peak period the proposed robust timing plan overall performs slightly worse than the adaptive and time of day ones in terms of total delay but shows reduced total number of stops. In addition, it shows reduced average delay for the majority of the intersections in the subject signalized arterial (Figure 2).

Similar to the AM peak period, the proposed signal timing plan causes high average delays for movements with very high volume variations during the PM peak (SB left movement on PCH at the intersection with Topanga Canyon Blvd and the PCH NB through movement at the intersection with Entrada Drive).

Total Delay (hrs)					
	Adaptive	Time of Day	Robust	Adaptive (PM Peak Incident)	Robust (PM Peak Incident)
AM Peak	533	488	495		
PM Peak	528	513	547	528	552
Total Number of Stops					
	Adaptive	Time of Day	Robust	Adaptive (PM Peak Incident)	Robust (PM Peak Incident)
AM Peak	37,815	39,748	36,288		
PM Peak	38,764	38,412	36,525	38,674	37,404

Table 1: Total delays and number of stops for all signal timing plans tested.

Overall, the proposed robust signal timing plan appears to be able to accommodate a variety of demands and seems to be performing similarly and in some cases better than the existing adaptive signal timing plan and the time of day plans. This suggests that a timing plan that has been calculated based on weighted averages of hourly volumes for the whole day (or a chosen portion of the day) can be effective on signalized arterials with highly variable demand volumes.

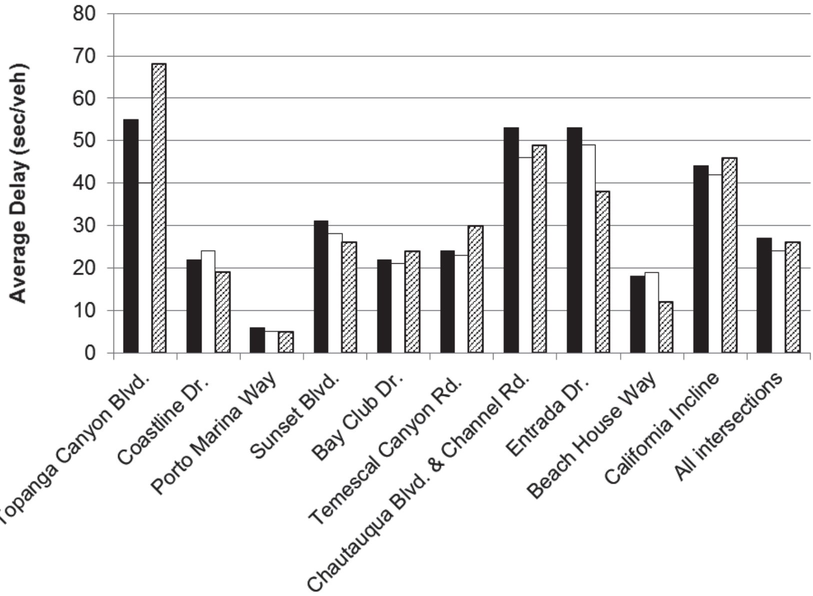

Figure 1: Comparison of adaptive, time of day, and robust signal timing plans for the AM peak: (a) average delay, and (b) average number of stops.

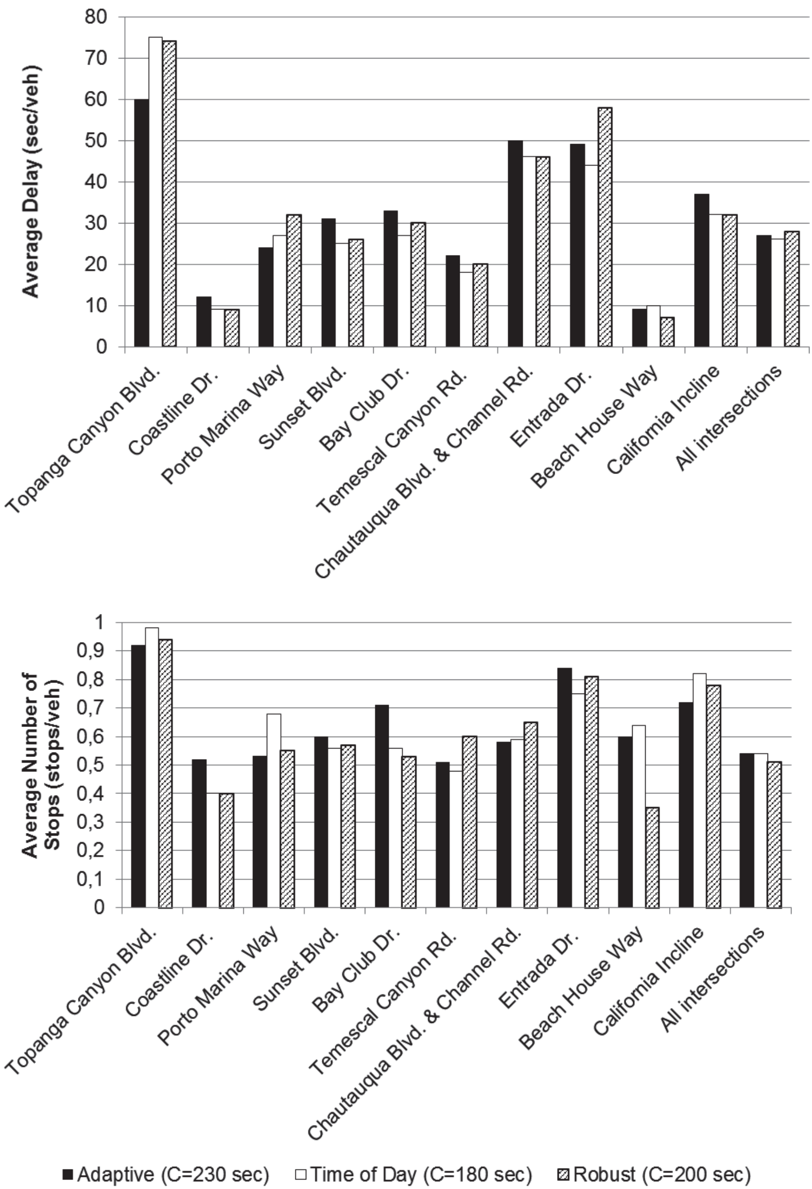

Figure 2: Comparison of adaptive, time of day, and robust signal timing plans for the PM peak: (a) average delay, and (b) average number of stops.

Demand and Saturation Flow Variability: Incident Occurrence

To investigate the performance of the proposed method under varying capacities, the following incident scenario was tested: reduction of saturation flow equal to ½ of a lane for the NB through movement of the PCH at the intersection with Temescal Canyon Road during the PM peak period. This scenario occurs fairly often because of events at the nearby schools. Under the incident scenario that was tested the adaptive signal timing plan for the PM peak period was updated to account for the reduced saturation flow by re-optimizing the splits at the intersection where the incident occurs.

Table 1 shows that the adaptive signal timing plan results in about 4% less total delay compared to the robust signal timing plan. Figure 3 compares the delays and stops for each intersection under the adaptive and robust plan for the incident scenario. The robust signal plan increased the delay compared to the adaptive control at the intersection of PCH with the Temescal Canyon Road, where the incident is located. Note that the robust plan had better performance at that intersection if one considers only the average delay under normal conditions (Figure 2). This implies that the adaptive signal control is more efficient in responding to changes in capacity commonly caused by incidents. Even though in this specific example we have assumed that the incidents were recurrent and the reduction in saturation flow was known, in the real world, incidents, especially non-recurrent ones, and their severity, cannot be predicted. This suggests that adaptive signal control is a more reliable system to utilize in high volume arterials where non-recurrent incidents can be often leading to oversaturated traffic conditions, queue spillbacks and high delays for all the travellers. The performance of the two plans for the rest of the intersections was similar to the normal conditions scenario (Figure 2).

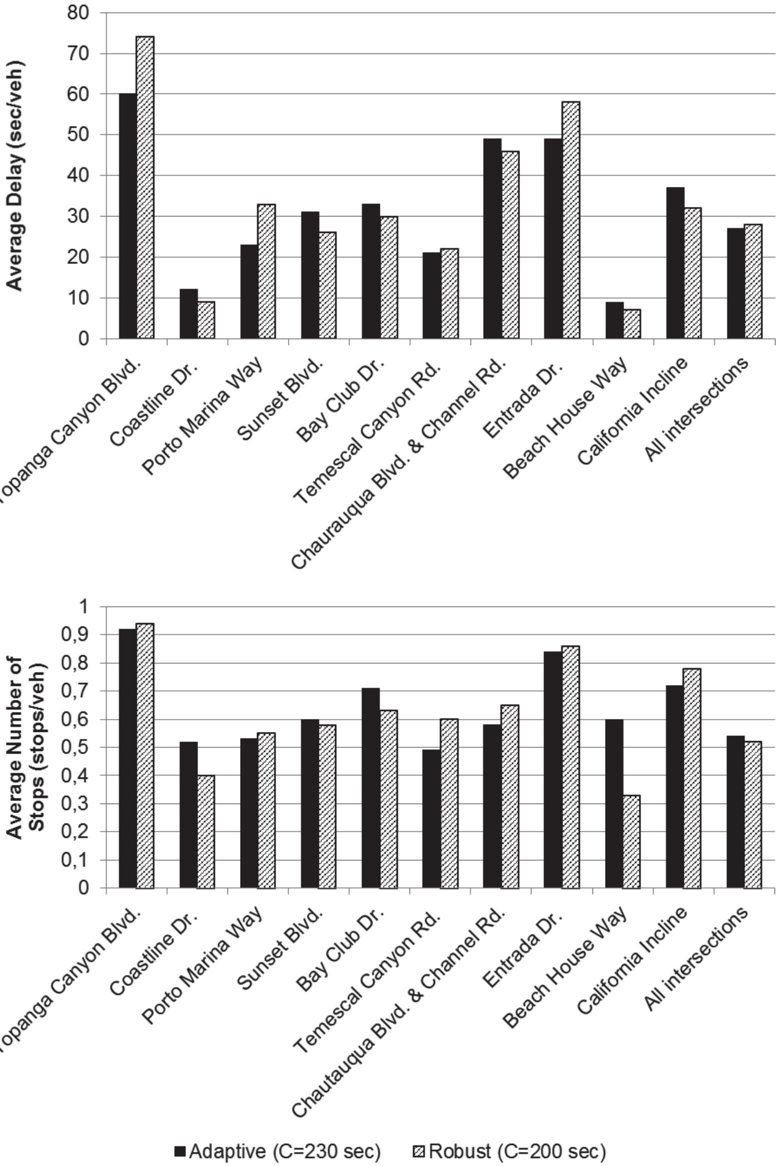

Figure 3: Comparison of adaptive and robust signal timing plans under incident conditions for the NB through movement on Temescal Canyon Road during PM peak: (a) average delay, and (b) average number of stops.

Conclusions

The paper presents a method to determine the appropriate demand volumes and capacities to be used for designing a single signal control plan for efficient operations on high volume arterials with high variability in demands and saturation flows over the day. The proposed method utilizes weighted averages of the hourly volumes and saturation flows reported for different time intervals over the day. The weighting factors are based on the portion of the day that these average hourly demands and capacities are observed over. After the weighted average values for demands and capacities have been calculated, the weighted intersection flow ratios can be obtained, the highest of which is used to calculate the optimal cycle length. This way, even though the proposed method does not guarantee that no oversaturated conditions will be observed, the probability of oversaturated movements is small for a wide range of traffic demands. Next, the offsets and splits are optimized based on the optimal cycle length and the weighted average demands and saturation flows determined before.

An application of the methodology has been performed on a ten-intersection signalized arterial located in South California, the Pacific Coast Highway. Tests have been performed for varying demands and capacities, the latter caused by the presence of recurrent incidents. The results indicate that the proposed method produces robust signal timing plans whose performance is comparable and for some intersections superior to the existing adaptive and the optimized time of day plans. The proposed robust signal timing plan may result in oversaturated conditions for a few movements with very high volume variability and peaking patterns. In practice, this can be addressed by adjusting the green times for those movements. Another observation made was that for some intersections the robust signal timing plan led to lower average number of stops than the other two plans but higher average delays, implying that vehicles were stopping fewer times but were waiting for longer periods. Considering that stops are directly associated with vehicle emissions, this can be seen as an advantage for using the proposed method versus an adaptive or time of day signal timing plan. When tests were performed for varying capacity conditions, the results indicated that adaptive signal control performs better because it is able to respond to incidents in real time providing more efficient signal timings.

In a nutshell, the proposed method can be used to develop robust signal timing plans that perform similarly to adaptive and time of day ones, without the need for expensive surveillance systems. However, adaptive control is more effective under non-recurrent incident conditions compared to the robust one, because it can respond to changes in capacity in real time. Future work includes testing the method on other arterials and comparing the performance of the proposed signal timing plans with other robust signal timing plans that have been proposed in the literature. In addition, we plan to investigate the performance of the proposed signal timing plans when they are developed to account for short term variations within one hour, for example the peak hour.

Acknowledgements

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An Input-Output Focused Approach to Characterize Freight Transport Models

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Abstract

The selection of an appropriate freight transport model for a specific research subject is based on a set of multidimensional criteria, as e.g. use-cases, geographical scope, methodological design, and input and output data of the model.

We made an attempt to characterise different freight transport models, with a focus on the relevant input and output data. For this attempt, we used the SADT modelling concept (because of its clear input-output focus and its simplicity in terms of symbols and syntax), and introduced a set of binary general differentiators of freight transport models.

We applied our characterization method to twelve selected freight transport models. The results of our approach may help other researchers to methodologically assess, which model(s) they might use, and which data these models require.

1. Introduction

1.1 Research Context

As part of a research task to objectively evaluate the potential of existing electric vehicle concepts to fulfil freight transport demand on the one hand and to quantify the benefits—or detriments—caused by replacing the existing vehicles with the new concepts on the other hand, a comprehensive quantitative and qualitative description of the freight transports in Singapore is needed.

1.2 The Problem

In order to be able to evaluate the different scenarios for implementing electromobility[1] concepts, we intend to build a suitable quantitative model for freight transport based on an

[1] The term "electromobility" refers to transportation through the means of electric-powered vehicles. For road transport, its current form ranges from the pure all-electric vehicle, such as the fuel cell vehicle and the battery electric vehicle, to various hybrid implementations, which include the parallel hybrid vehicle, the plug-in hybrid vehicle and the range extended electric

existing approach. Thus we need to choose an appropriate freight transport[2] model. As a basis for this choice, we want to characterise the known models in a way that aids our selection of an appropriate model for our research domain.

The criteria to characterize the different models are multi-dimensional. These dimensions include (but are not limited to) different use cases (from modelling existing goods traffic to forecasting of goods traffic based on different decision variable-sets), different geographical scopes (urban, regional, national or trans-national), different methodological designs (e.g. aggregate, disaggregate or hybrid approaches) and different input and output data, which includes differences on data entities as well as differences on data detail level.

Several attempts to characterize the different models have been proposed (see section 0), but we want to introduce a higher differentiation-detail-level for the characterization of the different models.

This paper presents in the following order:

- previous attempts to characterize and classify freight transport models;
- a detailed description of the methodology employed to characterize the models, based on the input-output modelling approach, and other important higher level indicators;
- one selected sample result to illustrate the potential of employing our approach;
- critical discussions regarding the methodology and the results of our approach;
- need for further research and the outlook.

2. Methodology

In this section, we want to provide a brief overview on known characterization and classification attempts, motivate the focus of our research, and introduce the methodology we have applied.

2.1 Known Characterization Attempts

In this sub-section, some of the more prominent and recent attempts to characterize or classify goods transport models are discussed.

De Jong et al. [2] and Tavasszy [3] described freight transport models in terms of the major stages involved, which is reminiscent of the ubiquitous passenger transport model framework, the four step algorithm. De Jong et al. [2] reviewed national and international freight transport models, further decomposing them into the four primary model functions (see **Table 1**). Within these lower-level “models”, the methods employed are discussed and analysed for their advantages and disadvantages. However, de Jong et al. [2, pp. 105] point

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vehicle as mentioned in the report by e-mobil BW GmbH [1, pp. 8-9].The concept may also be expanded to include catenary-powered vehicles and two- or three-wheelers.

[2] Note on terminology: as commercial traffic includes both traffic induced by transport of goods (i.e. freight transport) and traffic induced by commercial and public service operations. We either refer to "goods traffic" or "service traffic" in the following sections.

out that "transformation modules" which do not fall in any of the four categories, are needed to support the four-step algorithm.

Tavasszy [3, pp. 49] introduces an alternative framework to the four-step algorithm, which is more specific to freight transport modelling (see **Table 1**). This is a process-based analysis, similar to de Jong et al. [2]. Notably Tavasszy introduces precision in the terminology of the stages, such that the distinction in decision-making between freight transport and passenger transport is clear.

De Jong et al. [2, pp. 105]	**Tavasszy [3, pp. 49]**
I. Production and Attraction,	1. Production and Consumption,
II. Distribution,	2. Trade (Sales and Sourcing),
III. Modal Split, and	3. Logistics Services,
IV. Assignment.	4. Transportation Services, and
	5. Network Services.

Table 1: Stages in the framework introduced by de Jong et al. [2, pp. 105] and Tavasszy [3, pp.49]

A classification attempt was introduced in the National Cooperative Highway Research Program Report 606 by Cohen et al. [4]. Their freight forecasting toolkit describes five different model types, differentiated primarily by the combination of stages within each model. This allows the "transformation modules" mentioned by de Jong et al. [2, pp. 105] to be included, thus keeping a more consistent description of the models.

Cohen et al. [4]	A. Direct Facility Flow Factoring Models
	B. Origin-Destination Factoring Models
	C. Truck Models,
	D. Four-Step Commodity Models
	E. Economic Activity Model
Chow et al. [5]	F. Logistics Models
	G. Vehicle Touring Models

Table 2: Model classes introduced by Cohen et al. [7] and by Chow et al. [8]

Chow et al. [5] do highlight the trend of recent models by introducing two new model classes (see **Table 2**).

Other reviews on freight transport model literature focused on descriptive indicators and distanced themselves from classification of models. Gonzalez-Feliu and Routhier [6] and Anand et al. [7] provided a comparison of the different models from an applications perspective, which included broad characteristics of the reviewed models. De Jong [8] highlighted the inclusion of various logistics decision-makers simulated by models and described the models in terms of aggregated, disaggregated or aggregated-disaggregated-aggregated approaches. Zhou and Dai [9] attempted a multi-criteria analysis based on generic model characteristics, which were consolidated from various literature resources.

2.2 Input-Output Focused Approach

If goods traffic models shall be distinguished, one may look at “what they are used for” (e.g. use cases, geographic scope, etc.) or “how they are built”. Both perspectives are relevant for our problem, but the perspective of “what they are used for” has to cope with a wider range of interpretation freedom. In other words: how can one deduce a possible application of a model based on application references only, without knowing the construction of the model in greater detail?

Thus we firstly focused on the “how they are built” perspective. This perspective entails, on the one hand, the methodological or algorithmic “mechanism” of the model, and on the other, the data needed to feed the model (i.e. input data), as well as the data generated by the model (i.e. output data).

In order to reduce the complexity and to develop a generic approach to characterize the different models, we decided to focus on the model’s input- and output data first. At a later stage, we intend to dissect the “mechanisms” of the model.

2.2.1 Modelling Language Choice

Several modelling languages have been developed to systematically depict the “mechanisms” of *processes* as well as the required input- and output data. In this section, we will rationalize our modelling language method.

Different process- and data-flow modelling languages have been established in the past. ARIS (Architecture of Integrated Information Systems), IDEF (Integration DEFinition) and UML (Unified Modelling Language) to name but three can be considered as “state of the art” modelling languages. All three provide an in-depth modelling power of processes and data by different model conventions. Still, the in-depth modelling power goes hand in hand with the symbol and syntax complexity of these modelling languages. Our search for a simple and top-level oriented modelling language leads us to an IDEF-predecessor named SADT (Structured Analysis and Design Technique) which we consider highly suitable for our purposes, because processes are represented only as a “black box”. Furthermore, it has a clear input-output focus and is relatively simple to employ, in terms of symbols and syntax.

2.2.2 Modelling Concept of SADT

SADT was introduced by Ross [10], and the key aspects of SADT can be depicted as follows:

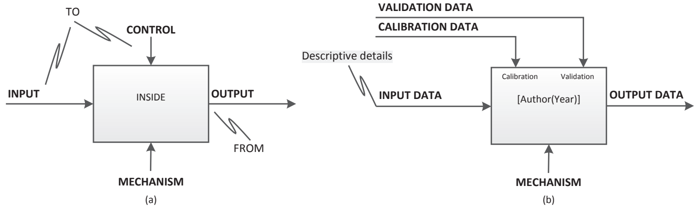

Figure 1: SADT Principle (Fig. 2(a)) by Ross [10, extract from Fig. 4] and our interpretation (Fig. 2(b))

The INSIDE can be considered as a “black box” process, such that only further analysis of the box would allow describing in detail, how the mechanisms of the model work methodology wise.

The INPUT and the OUTPUT can be interpreted as the input data and output data of the goods traffic models respectively.

The CONTROL can be interpreted as the control data for the goods traffic models, which in our case is the required calibration and validation inputs.

For the time being, the MECHANISMS within the goods traffic models are just roughly characterized as follows:

- Top Down “↓”. Models predominantly use highly aggregated data to derive traffic data from them. De Jong [8, pp. 360] uses the term “aggregated models”.
- Bottom Up “↑”. Models predominantly use many disaggregated data to condense them into traffic data. De Jong [8, pp. 361] uses the term “disaggregated models”.
- U-shaped “↺”. This aggregate-disaggregate-aggregate approach firstly breaks down highly aggregated data into estimates of disaggregated data, which are then condensed into traffic data. De Jong [8, pp. 361] uses the term “aggregate-disaggregate-aggregate models”.

Additionally, the SADT squiggle-symbol “ϟ” is used to add descriptive details on the input and output data.

2.2.3 Remaining Modelling Issues

If we had been using SADT-Models as key-elements of our characterization, only, some important aspects of our attempted characterization would remain unconsidered. These shortcomings are briefly discussed here.

Uncovered Details:

Our choice to focus on input-output-data and to depict the model “mechanism” as a black box only, results in the exclusion of a number of details. These details encompass *undefined data attributes* (e.g. input data are modelled by aggregated data names only and not by complete input data models) as well as not explicitly defined *intermediate data processing* steps.

The first issue of undefined *data attributes* can generally be accepted, as our approach aims at providing a top level characterization of the different goods traffic models. Still, as it will be pointed out later, not all data-detail aspects can be excluded per se.

The second issue of *intermediate data processing* is not trivial. In many goods traffic models some input data require a “pre-processing” before they can be fed into the model. The delimitation of “what is pre-processing” and “what is processing within the model” is the crux of the matter and will be discussed in Section 0.

In order to consider both issues (data attributes and intermediate data processing) without adding too much complexity to our modelling, we used the SADT “squiggles” to characterize the data in more detail within the SADT-models.

Uncovered Higher Abstraction Level Aspects:

Goods traffic models may also differ on a higher level of abstraction than the level we have modelled by means of the SADT-diagrams. Thus we added an auxiliary means of characterization in addition to the SADT-models, the factsheets.

2.3 Factsheets as Auxiliary Characterization Means

We detected a number of criteria, which may be used to differentiate the various goods traffic models. We grouped these criteria in a number of workshops and finally listed these criteria in a uniform factsheet-format. We consider this set of criteria as helpful to characterize the different goods traffic models, but we do not claim that this set of criteria is complete. The set of criteria is the following:

2.3.1 Geographical Scope

Different goods traffic models have been designed for different geographical scopes: *Urban Models* (which focus on the goods traffic within city limits or within metropolitan areas), *Regional Models* (which encompass a significantly larger geographic scope than just one urban area), *National Models* (which encompass the whole goods traffic of a country and a significantly larger geographic scope than just one region) and *Inter-National Models* (which encompass goods traffic of several adjacent countries).

This categorization is not unique, as some models may be used for different geographical scopes, and thus one model may qualify for different geographical scopes. The geographical scope also needs to be interpreted by the subsidiarity-principle (e.g. a model suited for Singapore or Monaco would need to qualify as an urban model rather than a national model).

2.3.2 Modal Scope

Different goods traffic models cover different sets of transport modes. Thus we chose to use a binary 6-digit vector to show, which transport mode is covered by the model: road, rail, inland waterway, sea, air and/or pipeline.

2.3.3 Object Scope

Some freight transport models are designed for goods traffic only, others include person traffic for commercial reasons (i.e. services) too. Thus we chose to use a binary 2-digit vector to show, which objects are covered by the model: "commercial goods transport" (resulting in goods traffic) and "person transport for commercial reasons" (resulting in service traffic). Service traffic is induced by ambulances, the police, repairmen & salesmen traveling within their work-hours (excluding getting to work and back) etc.

2.3.4 Road Transport Differentiation

A simple way to differentiate road transports is the concept of *Vehicle Types*. Introducing light, medium, and heavy vehicles[3] is one possible way to model differences in transport

[3] Hunt and Stefan [11] use vehicle classes to differentiate the transports.

execution with reference to different transport capacities. Still, using these vehicle types only, does not fully account for the structural differences in road transport execution.

In the domain of logistics these structural differences are commonly represented by *Transport Execution Patterns*:

Full truck load (FTL) – often executed by heavy vehicles
Less-than-full truck load (LTL)—often executed by heavy and medium vehicles
Groupage – often executed by medium and light vehicles
If goods traffic shall be modelled in greater detail, these differences in tour structure have a significant impact on how the transport volumes are converted into goods traffic loads.

2.3.5 Cargo Differentiation

Different cargo is transported by different transport execution patterns. The question of "which cargo is transported how" can often be determined on an individual order-level only. Still many models use an auxiliary, highly aggregated differentiator, which helps to model the influence of "what is transported" on "the way how things are transported". Commonly used auxiliary differentiators are:

- Shipment Size
  Similar to the rough differentiation of vehicle types, a rough[4] differentiation of *Shipment Sizes* can be employed. A different concept (based on the load handling in logistics operations) which is closely related to shipment size is the concept of *Handling Units* which allows differentiation by *Bulk* (as often found in primary industry transports – usually FTL transports), vs. *Container* (usually FTL transports, if 40' or 45' containers are transported or LTL transports, if 20' containers are transported), vs. *Pallet* (usually resulting in FTL or groupage transports) vs. *Item* (i.e. non-palletized goods – depending on item size, this handling unit may result in FTL, LTL or groupage transports). Still, in our characterization we considered the concept of handling units to be a variant of the shipment size concept.
- Industry Sector[5]
  Differentiation depth by industry sector, if used within goods traffic models, can vary a lot. Typical industry sector definitions used within the goods traffic models are for instance based on NAICS (North American Industry Classification System) as specified by the US department of commerce or NACE (Nomenclature statistique des activités économiques dans la Communauté européenne) as specified by the European Commission. Still, many goods traffic models only use a proprietary, model specific grouping of these industry sectors to reduce complexity.

[4] It is rough because the distinction of shipment sizes is often done by a rough volume- or weight-based metric only.
[5] Some authors use the term "Economic Activity" instead of "Industry Sectors". We deem both terms sufficiently equivalent.

- Product Class
  Differentiation depth by product class, if used within goods traffic models, can also vary a lot. Typically used product class definitions are for instance CPA (Classification of Products by Activity) as specified by the European Commission or NST-2007 (Nomenclature uniforme des marchandises pour les statistiques de transport / Classification system for transport statistics) as specified by the United Nations Economic Commission for Europe (UNECE). Again, many goods traffic models only use a proprietary, model specific grouping of these product classes to reduce complexity.
- Value Chain Steps
  Cargo can be differentiated by where its transport is situated within the value chain (see **Figure 2**).

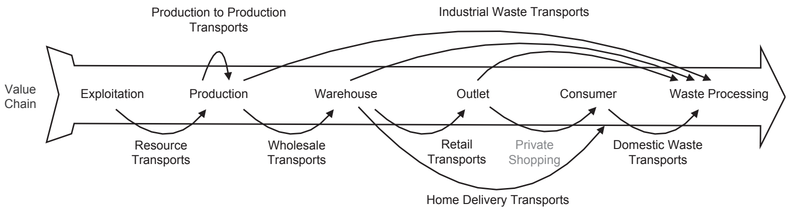

Figure 2: Value Chain Steps

- All transports within the value chain can be considered as goods transports except for the transports conducted by private shoppers, which belong to the domain of passenger transport.
- Behaviour Homogeneous Cargo Groups (BHCG)
  The concept of “behaviour homogeneous cargo groups”[6] clusters goods into categories, which behave similarly with respect to the way they are transported. We use the term to illustrate its similarity to the “behaviour homogeneous groups” (as introduced by Kutter [12])[7] in passenger traffic models.

2.3.6 Key Scaling Factors

In case goods traffic models shall be used for forecasting purposes, these models often use highly aggregated input data, which allow to scale the traffic volumes for different scenarios. As scaling factors we have detected: *Macroeconomic Key Figures* (these include, for instance gross domestic product, or input-output-accounts as e.g. import, export, production, consumption, etc.), *Consumption Figures* (these figures are computed at a disaggregated

[6] Note that the concept of BHCGs is significantly different to the other cargo differentiators. These also somehow try to differentiate cargo with respect to the way it is transported, but by grouping cargo by industry sectors, product classes or value chain steps, these groupings can be considered auxiliary groupings, which circumnavigate the nature of BHCGs.

[7] A very similar concept named “market segments” was propagated by Manheim [13, pp. 114-115].

level, and usually related to different sectors or product types; they are usually measured in volume units within the goods traffic models), *Population Figures* (these are usually related to different geographical areas and measured in headcount units, and then are converted into volume units within the goods traffic models) or *Employment Figures* (these figures are usually related to different sectors, they are measured in headcount units, too, and then are converted into volume units within the goods traffic models).

2.3.7 Uncovered Process Details

As of now, except for the very rough classification of the models into Top-Down (↓), Bottom Up (↑) and U-shaped models (↺) we have not included any further details on the process details or the algorithmic “mechanisms” of the different goods traffic models, yet. Once these “mechanisms” are analysed in greater depth, our fact sheets could be expanded to depict the characterization of the relevant model intrinsic mechanisms.

3. Results

The results of our approach produced three different objects—the *template* for the factsheet, the *content* of the factsheets, and a *structured overview* of the factsheet content for the models we analysed so far[8].

Figure 3 shows the factsheet template and an example of a factsheet content. The factsheet header includes the model name and the relevant literature reference. The factsheet body contains the top level differencing criteria and the SADT diagram. The layout is meant to give both a quick impression of what the model is about and provide information about the required input data and the generates output data. All current (and future) factsheets can be downloaded at

www.sv.bgu.tum.de / Publications

We encourage scientists, and especially the inventors of the models to check the factsheets and suggest improvements. We also invite inventors of currently uncharacterized models to submit factsheets for their models.[9]

Table 3 shows a structured overview of the information, which stems from the different factsheets. We have organised the table to start with the relevant model scope characteristics.

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[8] We have produced a total of 12 fact sheets for 12 different models so far.

[9] Communication details can be found through the URL-link above.

Model Name : Hunt & Stefan (2007)

Citation : Hunt, J; Stefan, K (2007): Tour-based microsimulation of urban commercial movements. In Transportation Research Part B: Methodological 41 (9), pp. 981–1013.

Geographical Scope	Modal Scope	Object Scope	Road Transport Differentiation	Cargo Differentiation	Key Scaling Factors
☐ Urban	☒ Road	☒ Goods Traffic	☒ Vehicle Types	☐ Shipment Size	☒ Macroeconomic Key Figures
☒ Regional	☐ Rail	☒ Service Traffic	☐ Full Truck Load (FTL)	☒ Industry Sector	☐ Consumption Figures
☐ National	☐ Inland Waterways		☐ Less than FTL (LTL)	☒ Product Class	☐ Population Figures
☐ Inter-national	☐ Sea		☒ Groupage	☒ Value Chain Steps	☒ Employment Figures
	☐ Airlines		☐ None	☐ Behaviour Homogeneous Cargo Groups	☐ None
	☐ Pipelines			☐ None	

Input-Output Data Entities:

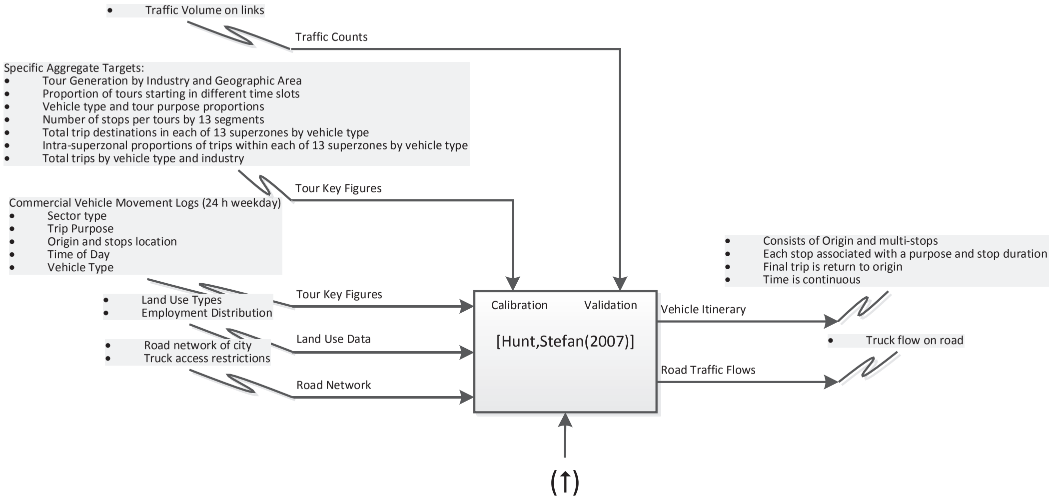

Figure 3: Factsheet for Hunt and Stefan [11]

			Wisetjindawat, Sano (2003)	Southworth (1982)	Boerkamps, van Binsbergen (1999)	Ogden (1978)	Hunt, Stefan (2007)	Hunt, Gregor (2008)	Gentile, Vigo (2007)	Mueller, Schneider (2009)	Tavasszy (1998)	DeJong (2010)	Liedtke (2009)	Holmgren et al (2012)
SCOPE COVERED	Geographical Scope	Urban	x	x	x	x								
		Regional					x	x	x					x
		National								x	x	x	x	
		Inter-National												x
	Modal Scope	Road	x	x	x	x	x	x	x	x	x	x	x	x
		Rail									x	x		x
		Inland Waterway									x			
		Sea									x	x		x
		Air									x	x		
		Pipeline			x						x			
	Object Scope	Goods Traffic	x	x	x	x	x	x	x	x	x	x	x	x
		Service Traffic					x							
DIFFERENTIATION ASPECTS	Road Transport Differentiation	Vehicle Types		x			x	x						
		Full Truck Load (FTL)			x	x		x		x	x	x	x	x
		Less-than FTL (LTL)											x	
		Groupage	x	x	x		x		x					
		None												
	Cargo Differentiation	Shipment Size												
		Industry Sector	x			x	x	x	x	x		x	x	
		Product Class											x	
		Value Chain Steps		x	x	x	x			x				
		Behaviour Homogeneous Cargo Groups									x			
		None												x
KEY SCALING FACTORS	Key Scaling Factors	Macroeconomic Key Figures					x				x	x	x	
		Consumption			x									x
		Population												
		Employment	x				x	x	x	x	x	x	x	
		None		x		x								
SADT-RELATED INDICATORS	Input	Tour key figures					x							
		Land Use data	x	x			x	x	x	x	x	x	x	
		Road Network				x	x			x			x	
		National Transport Statistics								x				
		National Economic Profile						x			x	x	x	
		Transport Network			x						x			x
		Consumption Data			x									x
		Production Parameters												x
		National Goods Classification							x					
		Trip Generation and Attraction				x								
	Output	Production and Consumption of Goods	x		x	x		x			x		x	
		Goods Flows	x		x	x		x			x	x	x	
		Orders												x
		Shipments	x									x	x	x
		Trip Generation and Atrraction		x					x					
		O-D Matrix	x			x			x					
		Vehicle Itinerary	x	x	x		x		x	x			x	
		Road traffic flows		x		x	x	x	x	x			x	
		Multimodal Transport Flows			x						x	x		x
	Calibration	Tour key figures	x	x	x	x	x		x	x	x		x	
		Commodity Flow Data						x				x		
		None												x
	Validation	Traffic Counts					x						x	
		Vehicle Kilometres								x				
		O-D Matrix	x											
		Tour Key Figures				x								
		Unspecified		x	x			x	x		x	x		
	Mechanism	Top-down "↓"		x		x		x	x	x	x			
		Bottom-up "↑"					x							x
		U-shaped "∪"	x		x							x	x	

Table 3: Structured Overview of Each Considered Model

4. Critical Discussion

4.1 General Discussion of Methodology

First of all, we are aware of the fact, that an attempt to *characterize* models is easier than a *categorization* attempt. We decided to go for a characterization approach rather than a categorization approach due to the many dimensions of model differentiation, which may be employed. We think it will be a challenge to come up with a simple, transparent and precise categorisation of models, as **Table 3** clearly depicts the big diversity within the set of considered models.

Second, there is a trade-off between *precision* of the characterization and the *simplicity* of the characterization. Colloquially phrased, our characterization attempt tries to find a balance between “read all literature on all cargo traffic models” (highest precision) and “there is one big bucket of goods traffic models" (highest simplicity). No matter how we do it, we would either lose precision or we would lose simplicity in our characterization scheme.

Third, our ex ante approach to *focus on the input/output data* of the different models was a choice rather than a finding. We think that this choice has proven beneficial, but we also think, that further research on characterizing the mechanisms within the models is needed.

Fourth, the *structure of the factsheet* may require some further research with specific attention to the questions a) are the differentiation criteria of the factsheets complete and b) is there an overlap in the differentiation criteria? One open aspect of completeness is the question: "Are the data required for the model obtainable?" And if yes at what cost (in terms of data purchasing costs – as well in terms of "how much effort is it to gather the relevant data") can these data be obtained? The aspect of overlaps within the differentiation criteria is most tangible between "cargo differentiation" and "road transport differentiation". These two criteria sets are not disjunctive, but intertwined.

Finally, considering that the methodology was developed based on 12 models, the robustness and flexibility to include other models is in question. This will be tested in the coming months with the expansion of our literature scope.

4.2 Methodological Choice to Leave Out Pre-Processing

One crucial methodological choice we made was to not introduce a pre-processing step for each goods traffic model. Still we want to show (see **Figure 4**) what difference this choice makes.

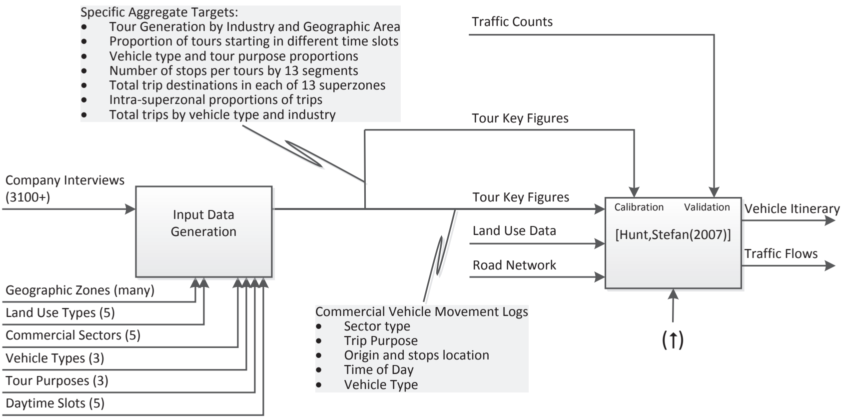

Figure 4: Hunt and Stefan [11] with the pre-processing step

Basically, the need to know the source of the input is secondary to the description of the input, at this stage of our research. However, what is designated as the main focus of the model is a question of viewpoint rather than a question of exact reasoning, as the following example shall illustrate.

Hunt and Stefan [11] require certain "tour key figures" (attributes or coefficients) for their model (e.g. the coefficient to model the ratio of delivery stops of a medium sized vehicle operating in a wholesale-context). These key-figures were derived from a large number of tour-diaries which have been captured by means of a survey. The question is, if the key-figures are the input data for the model or if the tour diaries are the input data for the model. What reportedly really went into the model were the diaries (converted into key-figures), but if these key-figures could have been generated by any other method, the model of Hunt and Stefan [11] could still work.

4.3 Discussion of Results

If meaningful comparisons between goods traffic models shall be made, similarities and dissimilarities of the relevant models should become transparent. Because we created the factsheet template, such *similarities and dissimilarities* of the models can be *detected*—at least within the characterizing scope of the factsheets (see the structured overview of models in **Table 3**). For example we see that many national goods traffic models can model FTL transports, but most urban models are able to model groupage transports.

The templates also *reduce bias* in the characterization, a) because the factsheet explicitly and objectively states what a model does, and b) because of the binary nature of our characterization attributes. Thus, the templates provide a basis for *falsification* of each model characterization (i.e. content of our factsheets), too. This is necessary for quality reasons, because there is a non- negligible risk of difference between what the creators of the models designed, how they presented it in their publications, what we understood and how we presented our understanding of the relevant models in the fact-sheets. To put our understanding into a format fit for falsification allows establishing a basis for *quality assurance*.

Our intention to generate a very precise characterisation by focussing specifically on input-output-data was only partly successful, because a) we found that focussing on the input-output data, only, was not enough to distinguish the different models sufficiently, and b) the issue of “data pre-processing” (see section 0.) opens room for interpretation on “what are input data”. Thus we lost some of the intended precision of our approach. Still, we consider the input-output-focussed results of our approach (i.e. the SADT-diagrams) robust enough to be of significant value.

5. Need for Further Research

First of all, as we have not looked into comparing and characterizing the model “mechanisms” in greater detail yet, we see the need for further research there. As of today, we think it would be useful to employ formal process modelling language elements for this purpose, such as UML-activity diagrams, IDEF3 or BPMN.

Secondly, we see a significant need for further research in the area of modelling “behaviour homogeneous cargo groups”. Many goods traffic models circumnavigate these missing BHCGs by using auxiliary structures such as industry sectors. Still, the uncertainty in such an auxiliary approach is almost intangible, as a) goods cannot easily be assigned to one sector (e.g. is the transport of food a part of NAICS-311 “Food Manufacturing”, NAICS-445 “Food and Beverage Stores” or NAICS-484 “Truck Transportation”?) and b) even if goods could clearly be assigned to one sector, they might still be transported in heterogeneous ways. For example, milk can be transported in bulk by tank truck using an LTL structure from farms to dairies, on pallets by trucks using an FTL structure from dairies to central warehouses, or on pallets by trucks using a groupage structure from central warehouses to supermarket outlets. The other auxiliary approaches, such as handing units, product classes or supply chain steps face similar problems. We therefore consider the topic of identifying "behaviour homogeneous cargo groups" as a topic which should be researched in further detail.

6. Outlook

Goods traffic models have grown not only in number but also in the variety of their design. Authors try to incorporate more freight transport specific elements in their models, even if data availability remains the predominant reason for using "auxiliary" concepts. Considering newly developed technologies (especially low cost "track & trace" and "big data processing") we consider it a realistic possibility, that new models will be invented shortly, which use mass capture of route-tracks of goods transport tours in a new design of bottom up models.

7. Acknowledgement

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8. Glossary

Order: A (transport) order specifies the need of a cargo to be transported from a point of origin to a destination in a given timeframe.

Route: The sheer geographical path of a vehicle conducting a tour through a road network (i.e. an uninterrupted sequence of road segments – which may e.g. be used for navigation purposes)

Shipment: A shipment is a pre-combined set of (smaller) orders (which share origin and destination and are handled as a batch), a single order, or a part of a (larger) order (which needs to be broken up into different shipments due to order size exceeding the capacities of single vehicles). A shipment is assigned to a tour as a whole.

Tour: A tour is a sequence of stops where loading or unloading of shipments occurs. A tour starts and ends at the same home base. A tour may return to this home base several times per day, once a day, or less frequently (e.g. once a week). In some publications, a tour is also called a *trip* or a *route*.

- *FTL-Tour:* A tour which only carries full truck loads (FTL). Thus a FTL-tour consists of alternating loading and unloading stops. The home base of a FTL tour often is a logistics node (e.g. a depot or a harbour), but it may also be a suitable parking lot close to the living quarters of the truck driver. FTL-tours often are multi day tours.
- *LTL-Tour:* A tour carrying shipments which don't use the full vehicle capacity exclusively. Due to the possible combination of different shipments on one tour, loading and unloading stops don't necessarily have to alternate. (Home base and duration of LTL-tours are similar to FTL-tours)

- *Groupage-Tour:* Groupage tours are collection and/or delivery round trips, which start from a depot, serve multiple destinations and end at the depot (i.e. home base). In contrast to LTL, they usually carry smaller shipments, are local tours (i.e. not long distance tours) and usually return to the depot at least once a day for re-loading.

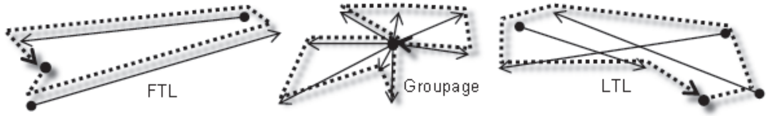

Figure 5: Distinction of FTL, groupage and LTL tours (shipments represented by arrows; tours represented by dotted lines)

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A macroscopic optimization model for the relocation problem of free-floating Carsharing Systems

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Abstract

The new free-floating Carsharing systems are not bound to stations and allow for one-way trips causing a certain imbalance between vehicle supply and demand. This paper describes a macroscopic optimization model for the relocation problem of free-floating Carsharing systems. Therefore, the business district of the Carsharing system is homogeneously subdivided into segments. Given the deviation between the current spatial vehicle distribution and the future optimum number of vehicles per segment, a relocation matrix is calculated by applying an optimization algorithm to the modeled minimum cost flow problem. This relocation matrix indicates the optimum vehicle movements between the segments which should be conducted by the operator. The objective of the optimization is a cost function that consists of time- and distance-related costs for the relocation actions. This function is minimized subject to several constraints. The model also integrates service depots where temporarily “superfluous” vehicles can be stored in case of a surplus in a segment or from which vehicles can be taken in case of a shortage of vehicles in a segment. Those service depots are necessary for the maintenance, cleaning and charging of (electric) vehicles. The benefits of the optimization are finally calculated for different example cases of a simplified test Carsharing system. The results show an increase of the profit for the Carsharing provider by up to 68% for the example scenarios.

Introduction

The new mobility concept of Carsharing increased remarkably during the last four years. This was basically due to the new so-called free-floating Carsharing systems that supplemented the traditional station based systems. The new systems are more flexible due to the possibility of one-way trips. The provider defines a business district in which the customer is not bound to stations. The vehicle can be left at any parking spot within this area. Mostly, the prize model is composed by a fixed registration fee and a fixed time-dependent usage rate as well as a lower time-dependent rate for parking. One obvious explanation for the success of those new concepts is the straightforward access to the vehicles without booking. The nearest vehicles available can be looked up using a smartphone app or the internet and can immediately be used by the customer.

Empirical studies indicate that Carsharing systems contribute to solving problems in transportation, land use, environment and society. Some of those evidences are summarized in [9]. It is worth mentioning that Carsharing reduces vehicle ownership by nine to 13 vehicles per Carsharing vehicle (cf. [7]). This reduction leads to positive modal shifts and increased multimodal and connected mobility. Moreover, Carsharing lowers net annual greenhouse gas emissions and average vehicle kilometers travelled (cf. [6]).

For a successful operation of a free-floating Carsharing system, it is extremely important that there is at least one car in the vicinity of each potential user. This is however not guaranteed due to the one-way trips causing a certain imbalance between vehicle supply and demand. There are thus zones with a shortage of vehicles whereas other zones show a surplus. This deviation has to be eliminated by dynamically relocating vehicles from oversupplied to undersupplied regions. Until now, most operators do not intervene strategically online although this leads to higher benefits if the additional user trips strongly compensate the relocation costs.

During the last few years, the research in the area of Carsharing vehicle relocation focused on operator-based vehicle movements. Most algorithms were designed for station-based one-way systems, where vehicle stock imbalances occurred. Those algorithms are reviewed in [11]. Summing up, little research was done in the past on finding relocation models for fully free-floating Carsharing systems without stations. The focus has been mostly on station-based one-way Carsharing systems with relocations at the end of the day, similar to BikeSharing systems. However, the new systems have different dynamics that should be taken into account. Trips are usually shorter than within station-based systems and the number of trips per vehicle is thus higher. Imbalances might occur more often and relocations have to be conducted dynamically throughout the whole day. Weikl and Bogenberger therefore introduced a new integrated two-step model for optimal vehicle positioning and relocation in [11]. This new approach consists of an offline demand clustering that allows for the prediction of demand and thus the prediction of the optimal future state of spatially available vehicles. The online module of the approach measures the differences between optimal vehicle positioning and current positioning. A mesoscopic optimization algorithm combining a macroscopic and a microscopic relocation model finds optimal relocation strategies if necessary. The focus of this paper is on the description of the macroscopic part of the Online Optimization Module.

The macroscopic relocation problem of free-floating Carsharing systems is very similar to the so-called Empty Container Repositioning Problem (ECRP) in freight logistics. The imbalances in the usage patterns of containers for cargo result in a surplus or shortage of containers at ports (or container depots). Those imbalances can be removed by leasing/returning containers from/to a leasing company or by bringing/moving containers from/to other ports (cf. [10]). The same applies to free-floating Carsharing systems where imbalances could be eliminated by shifting vehicles between zones or getting/returning vehicles from/to service depots. Due to the similarity between the two problems, ECRP literature was reviewed in addition to the Carsharing based literature review in [11].

Shen and Khoong [10] divided the ECR problem into an intra- and an inter-regional planning problem. They suggested conducting the relocation at first on a regional basis and if imbalances still occur, to repeat the relocation on an inter-regional basis. The authors use a nearest neighborhood algorithm. Li et al. [5] developed a model that calculates optimum container relocation movements given the current state of spatially available containers and the future optimum container distribution. As containers are continuously moved by shippers in each period, shipper- based in- and outflows are considered in addition to the redistribution movements. Olivo et al. [8] applied a rolling horizon method for solving the ECRP. The authors suggest a graphical approach with arcs representing relocation routes, inventory links and decisions concerning the time and place to take containers from depots. The method is based on an hourly time-step in a dynamic network. Boile et al. [1] suggest that depots should be closer to ports with a high volume of supplies and demands, which first of all results in an allocation problem that has to be solved. Choong et al. [2] analyzed the effect of the length of the planning horizon when using a rolling horizon method for the ECRP. They found out that a long planning horizon causes a better container distribution for the earlier periods. In case of missing information for future periods, a shorter planning horizon is preferred. Dejax [4] suggests that the planning horizon should be long enough to include the next set of container arrivals and departures. Crainic et al. [3] found out that the length of the planning horizon should be limited to between ten and 20 periods since the number of decision variables in any period will be fairly large.

The outline of this paper is as follows: At first, the overall idea of the macroscopic relocation model is shortly explained. Second, the relocation problem is formulated mathematically and the cost function and constraints are described in detail. Finally, the macroscopic algorithm is applied to an example Carsharing system and the benefits of the approach are quantified.

Macroscopic relocation model

Let us suppose that the "business district" of a free-floating Carsharing system is subdivided into k sub regions (segments). Additionally, the system has l service depots where "superfluous" vehicles can be temporarily stored in case of a surplus in a segment or from which vehicles can be taken in case of a shortage of vehicles in a segment. Vehicles have to be brought to the service depots regularly for maintenance, cleaning and charging in case of electric vehicles. The general idea is a macroscopic optimization algorithm that acts on a segment level (see Figure 1). The input is the deviation between the optimum number of vehicles (predicted demand) and the current number of vehicles for each segment. The macroscopic algorithm answers the question on how many vehicles have to be relocated from which segment to which segment or from which segment to which service depot and vice versa. This algorithm considers operator-based relocations only. In a real-life implementation a microscopic relocation algorithm has to follow. Based on the results of the macroscopic algorithm, the microscopic relocation algorithm has to solve the relocation problem on an individual vehicle level. The results are optimum execution rules for the relocation process. First, it answers the question on which vehicle to relocate to which exact position based on the optimal macroscopic movements between segments. Second, it generates recommendations on which macroscopic operator-based relocation could be possibly replaced by a user-based relocation. User-based relocation strategies make use of different incentives or bonus models for the customers. As operator-based relocations are mostly more cost-efficient than user-based relocations, the replacement might lead to cost savings. Third, the microscopic algorithm also optimally assigns the relocations to the several relocation staff and computes the shortest path for those relocation plans. Finally, optimal prize models and optimal user target groups are generated in case of user-based relocations.

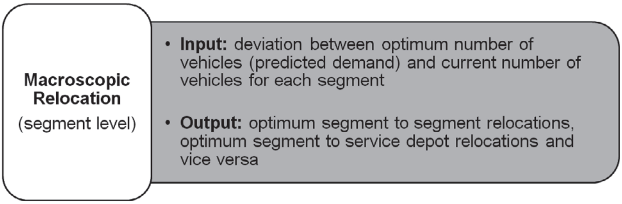

Figure 1: Macroscopic relocation algorithm

Let us assume that we know the current spatial vehicle distribution, which is given on a macroscopic level by the current number of vehicles per segment $c_i, i = 1{:}k$. The currently available fleet size of the Carsharing system is equal to the sum C of the number of vehicles per segment, $C = \sum_{i=1}^{k} c_i$. Additionally, the optimum future vehicle distribution is known for the current state and is also given on a macroscopic level by the optimum future number of vehicles per segment $f_i, i = 1{:}k$. The knowledge of future demand is derived by a cluster analysis of Carsharing demand using historical Carsharing booking data. This demand prediction is explained in detail in [11].

When comparing the currently available fleet size C to the total number F of vehicles demanded in the next period, three cases have to be distinguished:

The number of future demanded vehicles is

1. smaller than the currently available fleet size: $F = \sum_{i=1}^{k} f_i < C$
2. equal to the currently available fleet size: $F = \sum_{i=1}^{k} f_i = C$
3. greater than the currently available fleet size: $F = \sum_{i=1}^{k} f_i > C$.

In the first case, not all of the vehicles in the fleet are needed in the next time period. Those "superfluous" vehicles can be temporarily stored in a depot where they are maintained, cleaned and charged in case of electric vehicles. Those depots should preferably be near possible future hot spots, where they "wait" for and are more close to future demand. In the second case, in general no depots are needed neither for increasing nor for decreasing the number of available vehicles. If as in the third case, the number of currently distributed vehicles is smaller than the number of future requested vehicles, vehicles are taken from the service depot(s).

If those rules are kept, the number of requested vehicles is always equal to the number of currently available vehicles. Furthermore, as depots are located near hot spots, costs for future relocations from the depots to the hot spots are reduced.

Given the current number of vehicles per segment (the supply) as well as the optimum number of vehicles per segment for the next time period (the demand), the deviation between supply and demand can easily be calculated for each segment by $dev_i = f_i - c_i, i = 1{:}k$. Segments with positive deviation dev_i have a shortage of vehicles and are therefore called demand segments or under-supplied segments. Segments with negative deviation dev_i have a surplus of vehicles and are defined as supply segments or over-supplied segments. Segments with zero deviation currently have the optimum number of vehicles for the next time step.

The input of the macroscopic optimization algorithm is the deviation between the current and the optimum future vehicle distribution. The objective function of the optimization is a cost function that takes into consideration all the costs that occur when manually relocating vehicles between segments and/or between segments and depots. Based on this, an algorithm finds the optimum vehicle movements by minimizing the cost function. The question on how many vehicles should be relocated from which segments to which segments and/or from which segments to which depots and vice versa is solved. The relocation problem of free-floating Carsharing systems is thus a minimum cost flow problem that compares costs against the imbalance of supply and demand.

Let us consider a graph $G = (E, V)$ where the nodes V are the k segments of the Carsharing system and the edges E symbolize the movements of the vehicles between the different segments. The decision variables are thus the flows of vehicles between the nodes of the network. The costs of the edges are the total costs that occur when relocating a vehicle between the corresponding nodes. Those costs are explained in detail in the next section.

Figure 2 shows the in- and outflows of a node i of the graph $G = (E, V)$ for a Carsharing system with depots which are explained below.

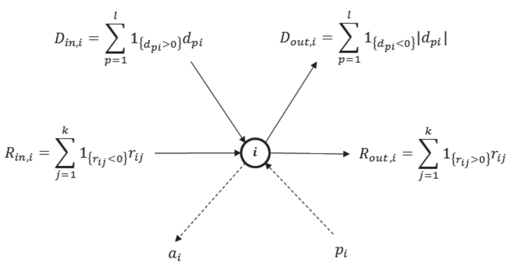

Figure 2: A node i of the relocation graph $G = (E, V)$ with the in- and outflows per time step.

One decision variable of the macroscopic relocation algorithm and thus the first variable of the cost function is an origin-destination matrix, the so-called relocation matrix R. This matrix indicates the optimum vehicle movements between the segments.

$$R = (r_{ij})_{i,j=1:k} \text{ with } r_{ij} = \begin{cases} n, & \text{if n vehicles are moved from segment } i \text{ to segment } j \\ -n, & \text{if n vehicles are moved from segment } j \text{ to segment } i \end{cases}$$

In case of existing depots, for each depot an additional node with arcs to each other node representing a segment is added to the graph. Let l be the number of depots of the Carsharing system. Vehicle movements between depots and segments are represented by the depot matrix

$$D = (d_{ij})_{i=1:l,j=1:k} \text{ with } d_{ij} = \begin{cases} n, & \text{if } n \text{ vehicles are moved from depot } i \text{ to segment } j \\ -n, & \text{if } n \text{ vehicles are moved from segment } j \text{ to depot } i \end{cases}$$

The corresponding costs of the depot arcs are the costs for getting a vehicle from/storing a vehicle in the depot that are explained in the next section.

Costs

Relocating Carsharing vehicles is connected to costs which should be minimal for the Carsharing provider. Those costs are grouped into two categories:

- relocation costs and
- penalty costs (opportunity costs).

The first type of relocation costs are the time-dependent relocation costs for the Carsharing personnel that relocate the vehicles. Let w be the hourly wage for the relocation personnel in Euros and let tt_{ij} be the travel time between the nodes i and j in hours. The personnel costs for relocating a vehicle from segment i to segment j are thus approximately equal to $w * tt_{ij}$. The same time-dependent costs also occur for vehicle movements between segments and depots.

The second type of relocation costs are the distance-dependent relocation costs for vehicle movements between segments or between segments and depots. Let fp be the fuel prize per kilometer in Euros, lv the loss of value of the vehicle per kilometer in Euros and $dist_{ij}$ the distance between two nodes i and j. The distance-related relocation costs for a vehicle movement between two segments i and j or a segment i and a depot j are thus

$$(fp + lv) * dist_{ij} .$$

Penalty costs (opportunity costs) are costs for demand that can't be met. Let g_i be the gain of an average Carsharing trip out of a specific segment i for the operator and let p_i be the number of currently missing vehicles in segment i. The penalty costs for segment i are thus equal to $g_i * p_i$. For the integration of penalty costs into the optimization model, an artificial node/segment with an infinite number of vehicles is connected via artificial arcs to each of the segment nodes. Those artificial vehicle movements are considered in the model by the penalty vector

$P = (p_i), i = 1{:}k, p_i \geq 0$ with $p_i = n$, if a demand of n vehicles can't be met in segment i.

The cost of those artificial arcs is equal to the penalty cost. The average gain g_i is calculated for each segment using historical Carsharing booking data. It is the product of the average trip time (in minutes) of trips originating from segment i and the gain of a trip minute for the Carsharing provider.

If the current number C of available vehicles is greater than the number F of future demanded vehicles, the relocation algorithm tries to store "superfluous" vehicles in the service depots for maintenance etc. if necessary. This is not always possible, because the capacities of the service depots are limited. To avoid violation of the optimization constraints, another artificial node with arcs to each segment is added to the model. The costs of the artificial arcs are set to zero, because no additional costs arise if vehicles cannot be stored in depots. Those artificial vehicle movements are considered in the artificial vector

$A = (a_i)_{i=1:k}, a_i \geq 0$ with a_i
$= n$, if n "superfluous" vehicles in segment i cannot be stored in a depot for capacity reasons.

Cost function

For finding the optimum relocation strategy, a cost function has to be defined. This cost function is based on the costs defined in the previous section. Based on this cost function, the most cost efficient relocation strategy is found by the algorithm. Let us consider a Carsharing system with k segments and l depots. The cost function of the optimization model is the sum of relocation costs between segments, relocation costs between segments and depots and penalty costs for demand that can't be met:

$$c(R,D,P,A) = \sum_{i=1}^{k}\sum_{j=1}^{k} 1_{\{r_{ij}>0\}} * r_{ij} * \left(dist_{ij} * (fp + lv) + tt_{ij} * w\right) + \sum_{p=1}^{l}\sum_{i=1}^{k} sgn\left(d_{pi}\right) * d_{pi} * \left(dist_{pi} * (fp + lv) + tt_{pi} * w\right) + \sum_{i=1}^{k} p_i * g_i + \sum_{i=1}^{k} a_i * 0 \quad (1)$$

Constraints

The optimization model has several constraints that have to be satisfied:

$$r_{ij} = -r_{ji} \ \forall \text{ segments } i,j = 1{:}k \quad (2)$$

$$\sum_{j=1}^{k} r_{ji} + p_i + \sum_{p=1}^{l} d_{pi} - a_i = dev_i \ \forall \text{ segments } i, i = 1{:}k \quad (3)$$

$$\sum_{j=1}^{k} 1_{\{r_{ij}>0\}} r_{ij} + \sum_{p=1}^{l} 1_{\{d_{pi}<0\}} \left|d_{pi}\right| - a_i \leq 1_{\{dev_i<0\}} |dev_i| \ \forall \text{ segments } i, i = 1{:}k \quad (4)$$

$$-\sum_{i=1}^{k} d_{pi} \leq cap_{d_p} - cur_{d_p} \ \forall \text{ depots } p, p = 1{:}l \quad (5)$$

$$\sum_{i=1}^{k} 1_{\{d_{pi}>0\}} d_{pi} \leq cur_{d_p} \ \forall \text{ depots } p, p = 1{:}l \quad (6)$$

$$p_i, a_i \geq 0 \ \forall \text{ segments } i, i = 1{:}k \quad (7)$$

$$r_{ij}, d_{pi}, p_i \text{ and } a_i \text{ integer } \forall\, i,j = 1{:}k, p = 1{:}l \quad (8)$$

First of all, the relocation matrix has to be skew symmetric, i.e. $r_{ij} = -r_{ij}, i,j = 1{:}k$ (see constraint (2)). This is obvious, because the number of vehicles moved from segment i to segment j is equal to the number of vehicles received by segment j from segment i. Second, all demand should (artificially) be met by relocating the vehicles according to the relocation matrix and the depot matrix and by considering the artificial vehicle movements for demand that can't be actually met. This is ensured by constraint (3). Third, constraint (4) represents the fact that the number of vehicles leaving a segment can't exceed the surplus of vehicles in this segment. Finally, a depot i has a maximum vehicle capacity cap_{d_i} that is not allowed to be exceeded as well as a current number cur_{d_i} of vehicles in the depot at the beginning of the optimization period. The sum of the number of vehicles arriving at the depot and the number of vehicles leaving the depot must not exceed the capacity cap_{d_i} minus the current number of vehicles cur_{d_i} in the depot (see constraint (5)). Additionally, the number of vehicles leaving the depot has to be smaller than the limited supply cur_{d_i} of vehicles in the depot during the optimization period. This is integrated into the model by constraint (6). The elements of the penalty vector P have to be positive integers (see constraint (7)), because penalty movements only occur in one direction (to the segments). Constraint (8) ensures that the elements of the relocation matrix R and the depot matrix D are integers because they represent whole vehicle numbers.

The following additional constraints (9) and (10) guarantee that all “superfluous” vehicles are stored in the depots as long as the depots have enough capacity and that vehicles are only taken from depots if $C < F$, i.e. if not all demand can be met by pure segment to segment relocations.

$$\sum_{p=1}^{l}\sum_{i=1}^{k} 1_{\{d_{pi}<0\}} d_{pi} = c_1 \text{ with } c_1 = \begin{cases} \sum_{p=1}^{l} cap_{d_p} - \sum_{p=1}^{l} cur_{d_p}, \text{if } C - F > \sum_{p=1}^{l} cap_{d_p} - \sum_{p=1}^{l} cur_{d_p} \\ C - F \text{ otherwise} \end{cases} \quad (9)$$

$$\sum_{p=1}^{l}\sum_{i=1}^{k} 1_{\{d_{pi}>0\}} d_{pi} \leq c_2 \text{ with } c_2 = \begin{cases} \sum_{p=1}^{l} cur_{d_p}, \text{if } F - C > \sum_{p=1}^{l} cur_{d_p} \\ F - C \text{ otherwise} \end{cases} \quad (10)$$

*Software Implementation*The optimization problem is modeled in MATLAB using the TOMLAB modeling class TomSym. It is solved in MATLAB by means of the TOMLAB optimization solver package CPLEX including simplex and barrier solvers.

Examples

Let us consider a simplified example Carsharing system with 9 segments, which are numbered consecutively from 1 to 9.

In the first example, the current spatial vehicle distribution is given by $c = [3, 1, 5, 2, 4, 0, 7, 3, 4]$ whereas the optimum future vehicle distribution is given by $f = [5, 1, 7, 0, 5, 2, 1, 3, 2]$. The current and the optimum future spatial vehicle distribution of the Carsharing system are shown in Figure 3.

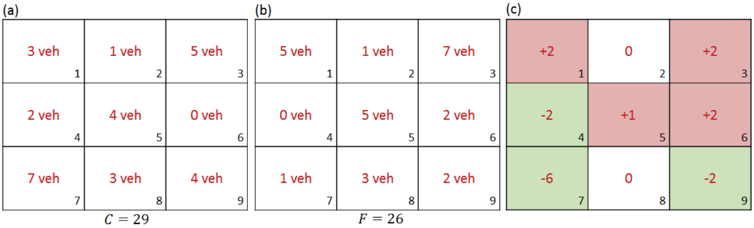

Figure 3: Spatial Carsharing vehicle distribution, (a) current state, (b) future optimum state; (c) resulting supply segments (negative deviation) and demand segments (positive deviation).

In Figure 3c, the resulting demand segments with shortages and thus positive deviation dev_i are marked in red whereas the supply segments with surplus and negative deviation dev_i are represented in green. The deviation vector is $dev_i = [+2, 0, +2, -2, +1, +2, -6, 0, -2]$. The number of currently available vehicles is greater than the number of future demanded vehicles ($C = 29$ and $F = 26$). The optimization with CPLEX gives the optimum relocation movements shown in Figure 4.

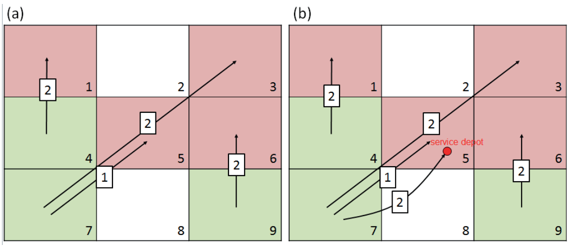

Figure 4: Optimum relocation movements for example 1, (a) without usage of the service depot, (b) with usage of the service depot

Let us first consider a period in which no maintenance, cleaning, charging etc. is necessary for the Car Sharing provider. Thus, possibly existing service depots are not considered for the relocations. The relocation algorithm then computes the following results (see Figure 3a). The shortage of two vehicles in segment 1 is eliminated by moving two vehicles from segment 4. The shortages in the segments 3 and 5 are removed by appropriate relocations from the supply segment 7. Finally, the demand of two vehicles of segment 6 is satisfied by getting vehicles from segment 9. All Carsharing demand can thus be met in the next time slice by conducting 7 vehicle relocations. The additional profit generated by the additional demand that can be fulfilled outweighs the additional relocation costs. The generated net profit exhibits an increase of 33% compared to when no relocations are applied.

Let us now consider a period in which service depots have to be used by the Car Sharing provider due to the necessity of maintenance etc. Let us assume that the considered Carsharing system has one service depot located in the hot spot segment 5 with a current number of vehicles $cur_d = 8$ and a capacity $cap_d = 10$ (see Figure 3b). The shortages in the segments 1, 3, 5 and 6 are eliminated by the same relocations as in the case without service depot. However, two of the three "superfluous" vehicles in segment 7 can be moved to the service depot where they are more close to possible future demand in hot spot segment 5 and where they can be stored for necessary maintenance, cleaning and charging in case of electric vehicles. Those vehicles can be moved to the service depot without the risk that future demand in the origin segment can't be met. Despite those additional two vehicle movements, the minimum total relocation costs are only slightly higher than in the case without service depot. The resulting profit for the Carsharing provider is 32% higher compared to when no relocations are conducted.

In the second example, the number of currently available vehicles is smaller than the number of future demanded vehicles ($C = 29$ and $F = 33$). The current spatial vehicle distribution is given by $c = [3, 1, 5, 2, 4, 0, 7, 3, 4]$ whereas the optimum future vehicle distribution is given by $f = [5, 1, 7, 0, 10, 4, 1, 3, 2]$. The optimization with CPLEX gives the optimum relocation movements shown in Figure 6.

Let us first assume that the service depot of the example Carsharing system currently doesn't have vehicles with completed maintenance etc. As no vehicles in the service depot are available for usage, the depot is not considered for the relocations. The relocation algorithm then computes the following results (see Figure 5a). The shortage of two vehicles in segment 1 is eliminated by moving two vehicles from segment 4. The shortage in segment 5 is removed by an appropriate relocation of the six "superfluous" vehicles from the supply segment 7. Finally, the demand of four vehicles of segment 6 is partially satisfied by getting two vehicles from segment 9. However, the remaining demand of two vehicles in segment 6 and the demand of two vehicles in segment 3 can't be met in the next time slice. In this case, total relocation costs caused by the 10 relocations and penalty costs arise. The additional profit generated by the additional demand that can be fulfilled outweighs the additional costs. The generated net profit exhibits an increase of 49% compared to when no relocations are applied.

Let us now again assume that the considered Carsharing system has one service depot located in the hot spot segment 5 with a current number of available vehicles $cur_d = 8$ and a capacity $cap_d = 10$ (see Figure 5b). The shortages in the segments 1 and 5 are eliminated by the same relocations as in the case without service depot. As before, the demand of four vehicles of segment 6 is partially satisfied by getting two vehicles from segment 9. The other two missing vehicles in segment 6 are now taken from the service depot as well as the two missing vehicles in segment 3. The increased number of 14 relocations causes higher relocation costs but as all demand can be met in the next time slice, no high penalty costs occur. The minimum total costs are therefore lower than in the case without service depot. The resulting profit for the Carsharing provider is 68% higher compared to when no relocations are conducted.

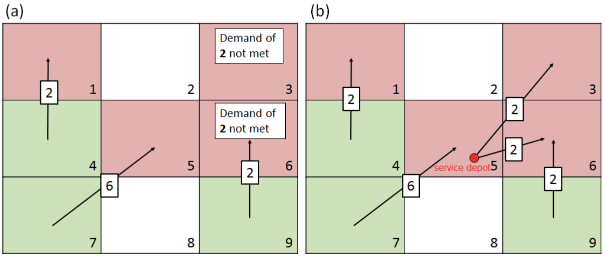

Figure 5: Optimum relocation movements for example 2, (a) without usage of the service depot, (b) with usage of the service depot

The profit for the Carsharing provider is shown for the different example cases in Table 1.

Framework	*Increase in profit (compared to no relocation)*
Example 1a: $C > F$, relocations, no depot usage	+33%
Example 1b: $C > F$, relocations, depot usage	+32%
Example 2a: $C < F$, relocations, no depot usage	+49%
Example 2b: $C < F$, relocations, depot usage	+68%

Table 1: Different frameworks and the resulting profit for the Carsharing provider.

Extensions and Upgrade

First, user-based in- and outflows that occur during the optimization period have to be taken into account. The relocation model described above tries to eliminate the deviation between current and optimum spatial vehicle distribution by finding minimum cost vehicle movements between segments and/or between segments and depots. The model assumes that during the period in which the operator-based relocations are conducted, vehicles are exclusively shifted by the Carsharing personnel. Vehicle relocations that happen due to user trips are not yet part of the model. Nevertheless, the relocation model can only recommend optimum relocations that lead to a balance of supply and demand, if also user-based relocations are taken into account. As future user trips are not known in advance, those have to be predicted based on real historical Carsharing booking data. Let $u_{in,i}$ be the predicted number of vehicles that are moved to segment $i, i = 1{:}k$ by users in the considered time period. Similarly, let $u_{out,i}$ be the number of vehicles that are moved out of segment $i, i = 1{:}k$ by user trips in the considered time period. Then constraints (3) and (4) convert to

$$\sum_{j=1}^{k} r_{ij} + p_i + \sum_{p=1}^{l} d_{pi} - a_i = dev_i - u_{in,i} + u_{out,i} \ \forall \text{ segments } i, i = 1{:}\,k \quad (11)$$

$$\sum_{j=1}^{k} 1_{\{r_{ij}>0\}} r_{ij} + \sum_{p=1}^{l} 1_{\{d_{pi}<0\}} \left| d_{pi} \right| - a_i \le 1_{\{dev_i - u_{in,i} + u_{out,i} > 0\}} \left| dev_i - u_{in,i} + u_{out,i} \right| \quad (12)$$

The adjusted in- and outflows of the graph $G = (E, V)$ are shown in Figure .

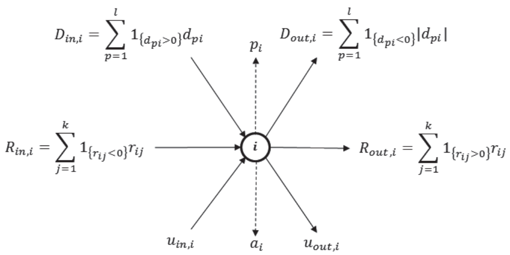

Figure 6: Operator- and user-based in- and outflows of a node i of the relocation Graph $G = (V, E)$.

Second, an essential aspect of a relocation model is the integration of local authorities who are thus able to define city-compatible guidelines for the Carsharing system. For instance, a maximum number of vehicles per segment can be determined by the city administration or segments can even be excluded from positioning vehicles therein. This ensures that Carsharing doesn't compete with public transport in areas of good public transport connection or that the parking situation is not even deteriorated in areas that have a shortage of parking spots. On the other hand, a minimum number of vehicles per segment defined by an authority guarantees mobility for people in areas with few public transport who might thus resign their own car. Additionally, it is possible that segments are temporarily not accessible due to street works, road closures, etc. and therefore even have to be excluded from assigning vehicle movements to them. Those requirements can easily be integrated into the optimization model by introducing additional constraints. An upper threshold ub_i and a lower threshold lb_i for the number of vehicles are defined for each segment $i, i = 1{:}\,k$:

$$ub_i = \begin{cases} n, & \text{if at most } n \text{ vehicles are allowed in segment } i \\ \infty, & \text{if there is no maximum number of vehicles in segment } i \end{cases}$$

$$lb_i = \begin{cases} n, & \text{if at least } n \text{ vehicles have to be available in segment } i \\ -\infty, & \text{if there is no minimum number of vehicles in segment } i \end{cases}$$

This additional constraint (13) is added to the optimization model by replacing $dev_i = f_i - c_i$ with

$$dev_i = f_i - 1_{\{f_i > ub_i\}} * (f_i + ub_i) - 1_{\{f_i < lb_i\}} * (f_i + lb_i) - c_i \tag{13}$$

Third, in most of the situations it will not be possible to meet the optimum demand in every segment due to the limited fleet size or due to the limited relocation personnel. The consequences are however not the same for every segment. There are segments where supply and demand should be relatively balanced. Those so-called meta segments are for instance segments with a high number of points of interest (sights, shopping malls), hot spots of traffic and public transport or congested urban areas. Segments that provide a good visibility for the Carsharing cars in the streets are also suitable as meta segments.

Furthermore, especially segments with a high number of parking spots and a relaxed parking situation could be prioritized for relocation. Therefore, a relocation model should provide the possibility to define segments of high priority that are privileged for relocation. This can be done by appropriately adjusting the penalty vector. Penalty costs for meta segments are higher than penalty costs for less important segments.

Fourth, the relocation model described above assumes that (if necessary) an infinite number of relocation actions can be conducted. This is however not possible in reality because for every Carsharing operator the number of relocation personnel is limited. Thus, the maximum number of relocation movements that can be conducted during a time period is limited. This limitation can be integrated into the model by adding constraint (14) that ensures that the sum of all vehicle movements between segments or between depots and segments does not exceed the limit lim of relocations that can be conducted by the relocation personnel in the considered time interval. The parameter lim is the product of the number of relocations that one relocation personnel is able to conduct in average in one time period and the number of relocation personnel that is available for the Carsharing provider in the considered time period.

$$\sum_{i=1}^{k}\sum_{j=1}^{k} 1_{\{r_{ij}>0\}} r_{ij} + \sum_{p=1}^{l}\sum_{i=1}^{k} |d_{pi}| \leq lim \tag{14}$$

Fifth, the model can be adapted to Carsharing with electric vehicles. The complexity of the system increases strongly when electric vehicles are integrated. Electric vehicles have to be recharged regularly and have to be brought to charging stations whenever necessary. This can be done either by the user or the Carsharing provider. The requirements of electric vehicles in Carsharing systems result in a complex logistic process that has to be optimized for minimizing costs. Most of the Carsharing providers will deploy depots like parking garages that are equipped with charging stations. Those depots can be integrated into the model by adjusting the service depots that we introduced for the base model described above. Additional constraints have to consider the battery levels of the vehicles, the number of free charging stations in the depot etc.

Finally, the introduced model is static. It is based on a static prediction of the Carsharing demand for the next time slice. However, Carsharing demand can suddenly change during the optimization interval due to external factors. This uncertainty of the demand forecast thus has to be considered in the relocation model. In case of a sudden change of the current demand, the future demand should be re-predicted and a dynamic re-optimization of the relocation strategies should be conducted.

Conclusion and Outlook

This paper introduced a new macroscopic optimization model for the relocation problem of free-floating Carsharing systems acting on a segment-level. The output of the macroscopic optimization algorithm indicates the optimum vehicle movements between the segments of the business district which should be conducted by the operator. The model also integrates service depots near Carsharing hot spots where temporarily “superfluous” vehicles can be stored for future demand in case of a surplus in a segment or from which vehicles can be taken in case of a shortage of vehicles in a segment. The service depots are located in hot spot areas of Carsharing demand and are needed for maintenance, cleaning and charging of the (electric) vehicles. The benefits of the optimization were finally calculated for different example cases of a simiplified test Carsharing system. First results are promising and show an increase of the profit for the Carsharing provider in all of the four example cases (up to 68% in the best case). For this first evaluation of the algorithm, two cases were distinguished.

First, if the number of currently available vehicles is greater than the number of future demanded vehicles, “superfluous” vehicles are stored in the service depots if maintenance etc. is currently necessary. This causes additional but however only slightly higher costs compared to when no service is needed and no service depots are considered. An advantage of the service depots results from the vicinity of the vehicles in the service depots to future hot spots.

Second, if the number of currently available vehicles is smaller than the number of future demanded vehicles, segment to segment relocations can eliminate shortages of vehicles only to a certain degree if no vehicles in the service depots are currently available. In case of service depots with available vehicles, all demand can be met if the number of available vehicles in the service depots is sufficient to remove the remaining shortages. The increased number of relocations causes higher relocation costs but as all demand can be met in the next time slice, no high penalty costs occur and the total profit is higher.

For future work, the algorithm has to be applied to a real Carsharing system. First, the extensions explained above have to be implemented. Second, historical current states of spatially available vehicles have to be generated from sequences of real historical Carsharing booking data. In addition, reliable demand models have to be generated that allow for the prediction of the corresponding optimum future state of spatially available vehicles (cf. [11]). Finally, for a real-life implementation a microscopic optimization model that outputs optimum relocation execution rules based on the macroscopic results has to be formulated mathematically.

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Intersection Fuzzy Control Modeling and Simulation: The Case of Beijing

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Abstract

In recent years, as the traffic congestion has been increasing serious in Beijing, many advanced transportation science and technologies have been proposed to solve the traffic problems. Intelligent control of intersection has been one of the major elements globally in the research on road traffic congestion. Based on the experience of engineering practice, this paper does research of intersection fuzzy control modeling and the fuzzy control optimization modeling based on neural network. Then, it puts forward the method of intersection fuzzy control design based on state automaton technology. Based on Matlab/VAP, it presents the method of intersection fuzzy control simulation modeling. Finally, making an actual intersection for an example, it compares the effect of timing control, induction control, fuzzy control, and neural network fuzzy control.

1 Introduction

For some intersections, since traffic flow changes in a certain rule, the fixed-time control method holds strong applicability. However, in Beijing City, because of the policy called Motor Vehicle Tail Number Restricted Driving, the traffic volumes vary greatly in different dates. The inherent defect of fixed-time control method may lead to the intersection capacity reduction. Combing with the fixed-time control method, induction control method can be adapted to the random changes in traffic flow. Nevertheless, induction control method is lack of effective system of quantitative analysis in the phase conversion decision.

With the development of intelligent control theory, traffic engineers generally concern on the intersection adaptive control based on intelligent control theory. The neural network method, genetic algorithm, and other intelligent algorithms are applied in traffic control [1].

Based on fuzzy control method, GAO J (2009) [2] designs the traffic signal two level fuzzy control system. Using the energy concept, Motawej F (2011) [3] studies a dissipativity-based approach to traffic signal control for an over-saturated intersection. LI Y (2011) [4] does some research about mechanism analysis and implementation framework for traffic Signal control of over-saturated intersection group. In view of the dynamics of traffic flow and the discrete characteristic of traffic signal, to optimize green time of isolated intersection, MU H (2012) [5] presents the traffic signal control method of isolated intersection based on Hybrid Petri Net. Using optimization algorithm, WU W (2013) [6] studies the design of left-turn phase for adjacent junctions.

In conclusion, all these works are basically based on intelligent techniques. While, we need simulation methods to evaluate the effect of intersection signal control. The simulation methods for intersection control can be roughly divided into two categories:

(a) Simulation method for research. These simulation methods are mainly based on Cellular Automata [7] or Multi-Agent [8].

(b) Simulation method for engineering application. These simulation method are mainly based on simulation software, such as Vissim [9], Paramics [10].

The choosing of simulation methods is one of the difficult problems in the course of the study. Especially, we should finish a large number of intersections signal control design in a short period of time.

As far as we know, we generally use simulation software to solve the engineering application problems. In fact, intelligent techniques also should be used for engineering application problems. Using some cases in Beijing, this paper analyses the characteristics of intersections and establishes the intersection fuzzy control and simulation model. By an actual case in Beijing, this paper shows the research process.

2 Intersection Fuzzy Control Modeling

2.1 Principle of Intersection Fuzzy Control

When traffic congestion occurs in an intersection, in order to ease traffic quickly and effectively, traffic police usually abandon timing control, and adjust signal control machine as the occasion demand of each traffic flow direction [11]. Traffic police make queue length of each intersection entrance lane, which can be directly observed, as the evaluation index. In the green light period, it needs to not only eliminate the queue of green light phase, but also ensure that the queue length of red light phase should not be too long. In general, traffic police consider the overall situation of intersection to determine the control scheme of the intersection. The conventional fuzzy controller of intersection is designed according to the above principle [12].

However, taking queue length as the single evaluation index holds some defects. Particularly, for these intersections, whose traffic flows of different directions are obvious different, the duration red time of the direction, whose traffic flow is low, maybe too long.

The model is built by comprehensively considering intersection queue length and red phase duration:

$$\begin{aligned} \min RN &= \sum \alpha_i RN_i \\ \min RT &= \sum \beta_i RT_i \end{aligned} \qquad (1)$$

in which, RN_i means the number of vehicles in the queue of red light phase in the ith flow direction, with the unit of veh/ln; RT_i means the duration of red light since the end of the last green light phase in the ith flow direction, with the unit of s; α_i , β_i are normalized indices.

In the process of solving the model, there are many ways to quantify the normalized indices. Plus, it is difficult to grant the balance between RN and RT. So we choose to use fuzzy method to simplify the problem.

① Make use of the queue length and red light duration of the red light phase to verify the pressing degree of waiting for green light. And by comparing the pressing degree of each red light phase, the alternative phase of the next green phase is decided;

② Make use the queue length and green light duration of the green light phase to verify the busy degree of certain green light phase;

③ The decision of whether lengthen current green phase or change phase is made based on current red phase and its pressing degree, along with the busy degree of green phase.

2.2 Intersection Fuzzy Control Model

The red phase choice model, green phase observation model and phase judgment model are built based on the urban intersection fuzzy control principal.

(1) Red light phase choice model

Make use of the number of vehicles in the queue of red light phase lane (RN, veh/ln) and red light duration since the end of last green light (RT, s) to judge traffic condition in all red phase and calculate pressing degree (RU) of each red phase and choose the alternative green phase (RZ) for next green light phase. The combination of input/output of the model is $(RN,RT)\rightarrow(RU,RZ)$.

① Choose 5 fuzzy subset $\{VS_{RN},S_{RN},M_{RN},L_{RN},VL_{RN}\}$, covering the domain of discourse for RN $[0,30]$, and the model of membership degree is:

$$\begin{cases} \mu_{VS}(RN)=f(RN,-6,0,6) \\ \mu_{S}(RN)=f(RN,0,6,12) \\ \mu_{M}(RN)=f(RN,6,12,18) \\ \mu_{L}(RN)=f(RN,12,18,24) \\ \mu_{VL}(RN)=f(RN,18,24,30) \end{cases} \qquad (2)$$

in which,

$$f(x,a,b,c)=\begin{cases} 0 & x\le a \\ \dfrac{x-a}{b-a} & a\le x\le b \\ \dfrac{c-x}{c-b} & b\le x\le c \\ 0 & x\ge c \end{cases} \qquad (3)$$

② Choose 5 fuzzy subset $\{VS_{RT},S_{RT},M_{RT},L_{RT},VL_{RT}\}$, covering the domain discourse for RT $[0,150]$, and the model of membership degree is:

$$\begin{cases} \mu_{VS}(RT) = f(RT,-30,0,30) \\ \mu_S(RT) = f(RT,0,30,60) \\ \mu_M(RT) = f(RT,30,60,90) \\ \mu_L(RT) = f(RT,60,90,120) \\ \mu_{VL}(RT) = f(RT,90,120,150) \end{cases} \quad (4)$$

③ Choose 5 fuzzy subset $\{VS_{RU}, S_{RU}, M_{RU}, L_{RU}, VL_{RU}\}$, covering the domain discourse for RU $[0,6]$, and the model of membership degree is:

$$\begin{cases} \mu_{VS}(RU) = f(RU,0,1,2) \\ \mu_S(RU) = f(RU,1,2,3) \\ \mu_M(RU) = f(RU,2,3,4) \\ \mu_L(RU) = f(RU,3,4,5) \\ \mu_{VL}(RU) = f(RU,4,5,6) \end{cases} \quad (5)$$

Red light phase choice model is a dual-input fuzzy controller. By summarizing the empirical experience of traffic police and expert, we get the principal of fuzzy controlling, which is if red light duration of a traffic flow increases or the arriving vehicle during the red phase increases, the pressing degree increases as a result. The principal could be expressed as

IF $\underset{\sim}{RN} = \underset{\sim}{RN_i}$ and $\underset{\sim}{RT} = \underset{\sim}{RT_j}$ then $\underset{\sim}{RU} = \underset{\sim}{RU_k} = \underset{\sim}{RU'_{ij}}$ $(i,j,k = 1,2,\cdots,5)$。

in which, $\underset{\sim}{RN_i}$, $\underset{\sim}{RT_j}$, $\underset{\sim}{RU_k}$ are the fuzzy subsets of RN, RT, RU respectively. The controlling principal of red light phase choice model is

$$\begin{cases} \underset{\sim}{RN} = [VS_{RN}, S_{RN}, M_{RN}, L_{RN}, VL_{RN}] \\ \underset{\sim}{RT} = [VS_{RT}, S_{RT}, M_{RT}, L_{RT}, VL_{RT}] \\ \underset{\sim}{RU} = [VS_{RU}, S_{RU}, M_{RU}, L_{RU}, VL_{RU}] \end{cases} \quad (6)$$

$$\underset{\sim}{RU'} = \begin{bmatrix} VS_{RU} & VS_{RU} & S_{RU} & M_{RU} & VL_{RU} \\ VS_{RU} & VS_{RU} & M_{RU} & L_{RU} & VL_{RU} \\ VS_{RU} & S_{RU} & M_{RU} & L_{RU} & VL_{RU} \\ S_{RU} & M_{RU} & L_{RU} & VL_{RU} & VL_{RU} \\ M_{RU} & L_{RU} & VL_{RU} & VL_{RU} & VL_{RU} \end{bmatrix} \quad (7)$$

These fuzzy set conditional statements can be concluded as

$$\underset{\sim}{R} = \bigcup_{ij} \left(\underset{\sim}{RN_i} \times \underset{\sim}{RT_j} \right) \times \underset{\sim}{RU'_{ij}} = \bigcup_{k=1}^{25} \underset{\sim}{R_k} \quad (8)$$

Calculate according to the combing rules of fuzzy inference, we can get the fuzzy set of controller change, denoted as $\underset{\sim}{RU}$

$$\underset{\sim}{RU} = \left(\underset{\sim}{RN} \times \underset{\sim}{RT} \right) \circ \underset{\sim}{R} \quad (9)$$

The output of fuzzy controlling $\underset{\sim}{RU}$ is a fuzzy subset, and shall be defuzzified which can be realized by weighted average and get corresponding controller RU^*:

$$RU^* = \frac{\sum_{i=1}^{n} \mu(RU_i) * RU_i}{\sum_{i=1}^{n} \mu(RU_i)} \qquad (10)$$

The output of red light phase choice model is shown as in Figure 1.

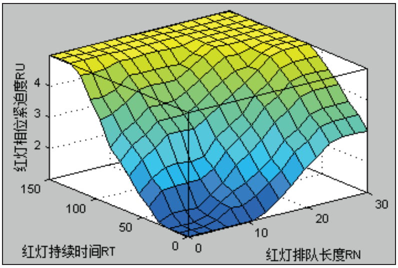

Figure 1: The fuzzy control results of red light phase choosing model

(2) Green light phase observation model

Make use of the maximum number of remaining vehicle during the green phase (GN, veh/ln) and green light phase duration (GT, s) to calculate the busy degree of green light phase (GU). The combination of input/output is

$$(GN, GT) \rightarrow GU$$

①Choose 5 fuzzy subset $\{VS_{GN}, S_{GN}, M_{GN}, L_{GN}, VL_{GN}\}$, covering the domain discourse of GN $[0,30]$, and the model of membership degree is

$$\begin{cases} \mu_{VS}(GN) = f(GN, -6, 0, 6) \\ \mu_S(GN) = f(GN, 0, 6, 12) \\ \mu_M(GN) = f(GN, 6, 12, 18) \\ \mu_L(GN) = f(GN, 12, 18, 24) \\ \mu_{VL}(GN) = f(GN, 18, 24, 30) \end{cases} \qquad (11)$$

②Choose 5 fuzzy subset $\{VS_{GT}, S_{GT}, M_{GT}, L_{GT}, VL_{GT}\}$, covering the domain discourse of GT $[0,120]$, and the membership degree model is

$$\begin{cases} \mu_{VS}(GT) = f(GT, -24, 0, 24) \\ \mu_S(GT) = f(RT, 0, 24, 48) \\ \mu_M(GT) = f(GT, 24, 48, 72) \\ \mu_L(GT) = f(GT, 48, 72, 96) \\ \mu_{VL}(GT) = f(GT, 72, 96, 120) \end{cases} \qquad (12)$$

③Choose 5 fuzzy subset $\{VS_{GU}, S_{GU}, M_{GU}, L_{GU}, VL_{GU}\}$, covering the domain discourse of GU $[0,6]$, and the membership degree model is

$$\begin{cases} \mu_{VS}(GU) = f(GU,0,1,2) \\ \mu_{S}(GU) = f(GU,1,2,3) \\ \mu_{M}(GU) = f(GU,2,3,4) \\ \mu_{L}(GU) = f(GU,3,4,5) \\ \mu_{VL}(GU) = f(GU,4,5,6) \end{cases} \quad (13)$$

Green light phase observation model is a dual-input and single-output fuzzy controller. By summarizing the empirical experience of traffic police and expert, we get the principal of fuzzy controlling, which is if green light overtime of a traffic flow increases or the remaining vehicles decrease, the busy degree decreases as a result. The principal could be expressed as

IF $GN = \underset{\sim}{GN_i}$ and $GT = \underset{\sim}{GT_j}$ then $GU = \underset{\sim}{GU_k} = \underset{\sim}{GU'_{ij}}$ $(i, j, k = 1, 2, \cdots, 5)$。

in which, $\underset{\sim}{GN_i}$, $\underset{\sim}{GT_j}$, $\underset{\sim}{GU_k}$ are the fuzzy subsets of GN, GT, GU respectively. The controlling principal of green light phase observation model is

$$\begin{cases} \underset{\sim}{GN} = [VS_{GN}, S_{GN}, M_{GN}, L_{GN}, VL_{GN}] \\ \underset{\sim}{GT} = [VS_{GT}, S_{GT}, M_{GT}, L_{GT}, VL_{GT}] \\ \underset{\sim}{GU} = [VS_{GU}, S_{GU}, M_{GU}, L_{GU}, VL_{GU}] \end{cases} \quad (14)$$

$$\underset{\sim}{GU'} = \begin{bmatrix} VS_{GU} & VS_{GU} & VS_{GU} & VS_{GU} & VS_{GU} \\ S_{GU} & S_{GU} & S_{GU} & VS_{GU} & VS_{GU} \\ M_{GU} & M_{GU} & M_{GU} & S_{GU} & S_{GU} \\ L_{GU} & L_{GU} & M_{GU} & M_{GU} & M_{GU} \\ VL_{GU} & VL_{GU} & L_{GU} & L_{GU} & L_{GU} \end{bmatrix} \quad (15)$$

These fuzzy set conditional statements can be concluded as

$$\underset{\sim}{G} = \bigcup_{ij} \left(\underset{\sim}{GN_i} \times \underset{\sim}{GT_j} \right) \times \underset{\sim}{GU'_{ij}} = \bigcup_{k=1}^{25} \underset{\sim}{G_k} \quad (16)$$

Calculate according to the combing rules of fuzzy inference, we can get the fuzzy set of controller change, denoted as $\underset{\sim}{GU}$ .After defuzzification which can be realized by weighted average, we can get corresponding controller GU^*.The output of green light phase observation model is shown in Figure 2.

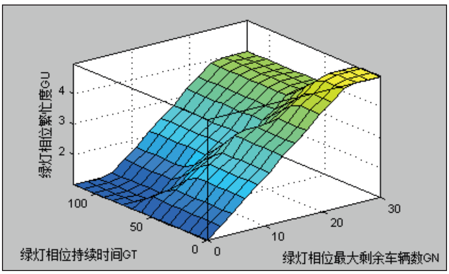

Figure 2: The fuzzy control results of green light phase observation model

(3) Judgment model

Make use of the pressing degree (RU) of red light phase (RZ) in red light phase choice model and the busy degree (GU) of green light phase in green light phase observation model to calculate the judgment degree (JU) and define that if $JU > 1.5$, traffic light switches to the most urgent red phase; otherwise, nothing happens. The combination of input/output of the model is $(RU, GU) \rightarrow JU$.

Choose 2 fuzzy subsets $\{NO, YES\}$, covering the domain discourse of JU $[0,3]$, the membership degree model is

$$\begin{cases} \mu_{NO}(JU) = f(JU,0,1,2) \\ \mu_{YES}(JU) = f(JU,1,2,3) \end{cases} \quad (17)$$

The judgment model is a dual-input and single-output controller. By summarizing the empirical experience of traffic police and expert, we get the principal of fuzzy controlling, which is if the pressing degree is high or the busy degree of green light phase is low, current green phase would be stopped and green light would be given to the alternative phase. The principal could be expressed as

IF $GU = \underset{\sim}{GU}_i$ and $RU = \underset{\sim}{RU}_j$ then $JU = \underset{\sim}{JU}_k = \underset{\sim}{JU}'_{ij}$ $(i, j, k = 1,2,\cdots,5)$。

in which, $\underset{\sim}{GU}_i$, $\underset{\sim}{RU}_j$, $\underset{\sim}{JU}_k$ are the fuzzy subsets of GU, RU, JU respectively. The controlling principal of phase judgment model is：

$$\begin{cases} \underset{\sim}{RU} = [VS_{RU}, S_{RU}, M_{RU}, L_{RU}, VL_{RU}] \\ \underset{\sim}{GU} = [VS_{GU}, S_{GU}, M_{GU}, L_{GU}, VL_{GU}] \\ \underset{\sim}{JU} = [NO, YES] \end{cases} \quad (18)$$

$$\underset{\sim}{JU}' = \begin{bmatrix} NO & NO & YES & YES & YES \\ NO & NO & NO & YES & YES \\ NO & NO & NO & YES & YES \\ NO & NO & NO & NO & YES \\ NO & NO & NO & NO & YES \end{bmatrix} \quad (19)$$

These fuzzy set conditional statements can be concluded as

$$\underset{\sim}{J} = \bigcup_{ij} \left(\underset{\sim}{GU}_i \times \underset{\sim}{RU}_j \right) \times \underset{\sim}{JU}'_{ij} = \bigcup_{k=1}^{25} \underset{\sim}{J}_k \quad (20)$$

Calculate according to the combing rules of fuzzy inference, we can get the fuzzy set of controller change, denoted as $\underset{\sim}{JU}$. After defuzzification which can be realized by weighted average, we can get corresponding controller JU^*. The output of phase judgment model is shown in Figure 3.

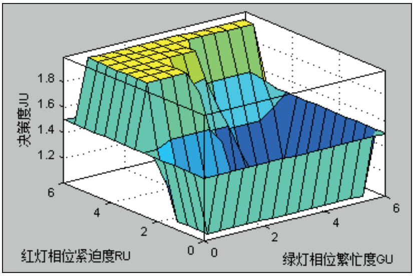

Figure 3: The fuzzy control results of justice model

2.3 Intersection Fuzzy Control Optimization Model Based on Neural Network

The achievement of fuzzy control principals, construction and adjustment of membership degree models count mainly on manpower and appeals strongly to the experience of designers and operators, which could be restricted sometimes and directly lead to failure of fuzzy controller design to find the best or second-best controlling performance. We induce neural network to the fuzzy system to replace manpower in dealing with complex intelligent work encountered in designing fuzzy controllers [10]. To overcome the defects of traditional fuzzy principals, we investigate the optimization method of urban intersection fuzzy control based on neural network.

Take red light phase choice model as an example, variables of the model RN , RT , RU each has 5 linguistic values. Every input unit of the neural network is corresponding to certain fuzzy subset of the input variable. Variable RN has 5 inputs corresponding to 5 fuzzy subsets, so does variable RT .

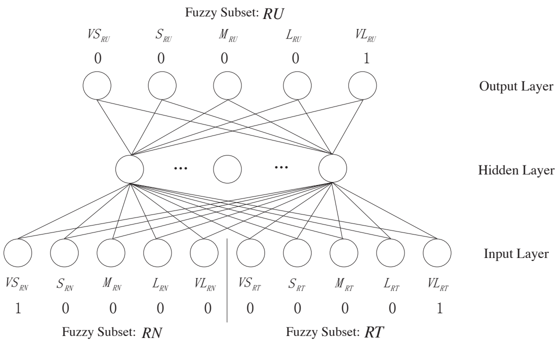

Figure 4: The structure of BP neural network

BP neural network with single-hidden layer can achieve any non-linear mapping with N -dimensional inputs and M -dimensional outputs, and has fine self-learning ability. We design a BP neural network fuzzy controller with single-hidden layer, whose structure shown in Figure 4.

The format of input signal $[\mu_{VS}(RN), \mu_S(RN), \mu_M(RN), \mu_L(RN), \mu_{VL}(RN), \mu_{VS}(RT), \mu_S(RT), \mu_M(RT), \mu_L(RT), \mu_{VL}(RT)]$ 。

Every output unit in the network is corresponding to a quantified value in the output variable space. And the output fuzzy subset can be denoted as the membership degree model of the quantified space. The format of output is

$[\mu_{VS}(RU), \mu_S(RU), \mu_M(RU), \mu_L(RU), \mu_{VL}(RU)]$ 。

The domain discourse of output RN is divided into 5 categories, as $\{0,6,12,18,24\}$; the domain discourse of output RT is divided into 5 categories, as $\{0,30,60,90,120\}$; the domain discourse of output RU is divided into 5 categories, as $\{1,2,3,4,5\}$. The input signal of the controlling rule, which is " RN is few and RT is long, then RU is high", can be denoted as $[1,0,0,0,0,0,0,0,0,1]$, in which $\mu_{VS}(RN) = 1$, $\mu_{VL}(RT) = 1$, and all the others are 0; the output signal is $[0,0,0,0,1]$, in which $\mu_{VL}(RU) = 1$, and all the others are 0.

The input level of red light phase choice model has 10 nodes, the hidden level has 13 nodes and the transmission function of the nerve cells in the hidden level is transig; the output level has 5 nodes and the transmission function of the nerve cells in the output level is logsig, while the training function is traingdx. We can get the training samples according to the input/output of red light phase choice model and fuzzy control principals. Every fuzzy principal is corresponding to a sample and the red light phase choice model has 25 dual-input samples. Training steps are set to be 1000 and the target error is restricted to 0.001. After 289 training process, we get the result meeting training requirement, as shown in Figure 5.

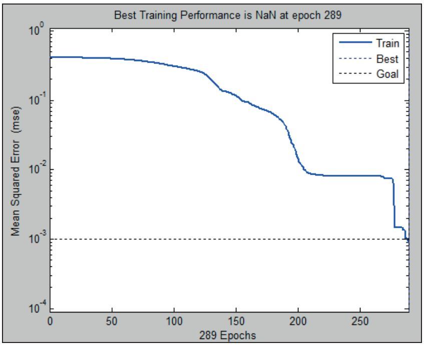

Figure 5: The neural network training result

Apply BP algorithm to the network training, so input signal is corresponding to target output. After training, the network can be seen as a container of fuzzy relations and if we want to get other conclusions from the network, the only thing needs to be done is input the real value after defuzzification.

The neural network fuzzy control of green light phase observation model and phase judgment model is similar to the one of red light phase choice model. The network meets requirement after training for 257 times and 167 times, respectively.

2.4 Design of Intersection Fuzzy Control Model Based on State automaton

The finite state automata is a five-term group

$$M=(Q,\Sigma,\delta,q,F) \quad (20)$$

in which, Q is the not empty finite set of states, Σ is the input alphabet, δ is the state transfer model, $\delta: Q\times\Sigma\rightarrow Q$, q is the original state of M, $q\in Q$, F is the termination state of M, $F\subseteq Q$, $\forall q\in F$.

For a standard four-phase cross intersection,

$$Q=\{state(1),state(2),state(3),state(4)\} \quad (21)$$

in which, $state(1)$, $state(2)$, $state(3)$, $state(4)$ is corresponding to the four phase. For a regular fixed-time control, the phases follow the circular sequence queue of $1\rightarrow2\rightarrow3\rightarrow4\rightarrow1$.

For intersection fuzzy control, it is possible for phase to jump. For instance, if some phases have high red light pressing degree, the phase can jump over the time when red light pressing degree is low and switch to green light beforehand. Of course, there is an outlier when there are left-turn waiting zone in the intersection and vehicles turning left are waiting in the zone. For safety reason, next green phase must dissipate the awaiting vehicles. So we can discuss in two situations.

(1) Without left-turn waiting zone

For intersections without left-turn waiting zone, phases can be calculated according to fuzzy control model.

State transfer model δ_l: state variable $state(i)$, input $incident(l)=\{JU>1.5,RZ=j\}$, output $state(j)$. When judgment degree is higher than 1.5, state changes.

(2) With left-turn waiting zone

For intersections with left-turn waiting zone,

①If state variable $state(i)$ is drive-through phase, there are 2 state transfer models.

State transfer model δ_m: state variable $state(i)$, input $incident(m)=\{JU>1.5,RN(j)\neq0\}$, output $state(j)$ $(j=i+1)$. When judgment degree is higher than 1.5 and there are vehicles in the left-turn waiting zone, state changes.

State transfer model δ_n: state variable $state(i)$, input $incident(n)=\{JU>1.5,RZ=j,RN(i+1)=0\}$, output $state(j)$ $(j\neq i+1)$. When judgment degree is higher than 1.5 and there are no vehicles in the left-turn waiting zone, state changes.

②If state variable $state(i)$ is left-turn phase, the state transfer model δ_k: state variable $state(i)$, input $incident(k)=\{JU>1.5,RZ=j\}$, output $state(j)$. When the judgment degree is higher 1.5, state changes.

3 Intersection Fuzzy Control Simulation

For urban intersection fuzzy control, simulation is a difficult point. We choose to use VAP as simulation tool. VAP programming language is used for dealing with normal induction control, but when it comes to self-adaptive control, VAP is not strong enough to deal with the complex algorithm and shall be assisted by other tools to realize the interaction between VAP control mechanism and fuzzy controller.

Off-line fuzzy controller design based on MATLAB can realize urban intersection fuzzy control according to experiences of the designer. To get rid of the restriction of designer to fuzzy control principal and membership degree model, we choose to use neural network training method to realize intersection neural network fuzzy control.

MATLAB can be used for fuzzy control modeling, yet how to achieve interaction between VAP and MATLAB remains a big problem. When using VAP for self-adaptive control, especially for fuzzy control, we can use MATLAB to design an off-line fuzzy controller and derive a fuzzy control input/output inquire table, and then use VAP to inquire from the table to realize intersection fuzzy control.

The process of urban intersection fuzzy control design and evaluation based on MATLAB and VAP is

Step1: Based on traffic characteristics of the intersection, design fuzzy controllers by MATLAB. Input all possible input values in the domain discourse and get corresponding output values to make an inquiry table.

Step2: Build VISSIM model and define detectors and traffic lights where necessary according to fuzzy control requirement. Form *.pua file and design phase transfer format.

Step3: When using VisVAP to define phase transfer principals, compare fuzzy variable values attained from detectors with the fuzzy control input/output inquiry table to get fuzzy output values, required for fuzzy control

Step4: Insert *.pua and *.vap files into VISSIM to realize urban intersection fuzzy control simulation and evaluation.

4 Case Study

Use VISSIM to evaluate vehicle average delay under four scenarios: fixed-time control (project 1), inductive control (project 2), dual-level fuzzy control (project 3) and neural network fuzzy control (project 4). The result is shown in Figure 6.

Compared to fixed-time control, inductive control solve the problem of overtime of south-north left turn green light, and decreases the delay on main road while increases that on the minor road. Two-level fuzzy control solves the problem of over-delay on the minor road on the basis of project 1. Neural network fuzzy control improves two-level fuzzy control by balancing delays of the intersection to decrease efficiency loss on the minor road caused by delay and enhance travelling efficiency on the main road at the same time.

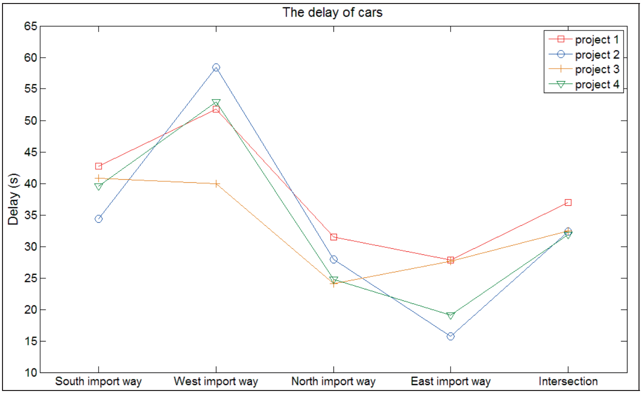

Figure 6: The evaluation of delay

In a word, control effect is inversely proportional to cost, that is neural network fuzzy control has the best control effect, while fixed control has the worst.

5 Conclusion

In this paper, we investigate urban intersection fuzzy control design and simulation modeling method. First, the red light phase choice model, green light phase observation model and phase judgment model are built and fuzzy control based on neural network is optimized. Then, fuzzy control method based on state automata is investigated and simulation process based on MATLAB/VAP is explained. Finally, a case study is carried out to compare control effects of fixed-time control, inductive control, dual-level fuzzy control and neural network fuzzy control. As the result shows, control effect is inversely proportional to cost, that is neural network fuzzy control has the best control effect, while fixed control has the worst.

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CTM Based Calculation of Number of Stops and Waiting Times

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Abstract

The Cell Transmission Model (CTM) is a numerical approximation of the shockwave theory. The CTM divides the links into discrete segments, known as cells, and updates the density of each cell (number of vehicles) after every second. Due to its simple formulations and high-speed execution, the CTM is considered advantageous for model-based Adaptive Traffic Control Systems (ATCSs). A CTM implementation was developed within Sitraffic Motion, the "Motion-CTM" [9]. The "Extended Motion-CTM" [11] calculates two performance indices for the online signal plan optimization in Sitraffic Motion: the number of stops and the waiting time. The Extended Motion-CTM introduces a new variable for every cell in the network, the Congestion Indicator (CI). The CI not only facilitates the calculation of the number of stops and the waiting time, but also assigns the calculated values to the appropriate signal. The significance of this novel idea is that it enables the calculation of signal related performance indices for the whole network in each second. The development of the CI algorithm in the form of a finite-state machine diagram is the core of this work. For the calculation of the number of stops, the CI is utilized to identify the cells at the end of the queue. Based on the outflow (vehicles per second) of these cells, the number of stops is derived. For the calculation of the waiting time, the CI is utilized to identify the cells that are in the queue. The waiting time is derived from the density of these cells and their outflow. The evaluation of the proposed algorithms shows that both the derived number of stops and waiting time are very close to the theoretical values obtained from the shockwave theory. Regarding the number of stops, the evaluation shows that the proposed algorithms perform much better than the approximation by Lin [10]. Regarding the waiting time, the evaluation shows that the delay calculation based on Almasri [6] and the waiting time in the Extended Motion-CTM give very similar results.

Introduction

The Cell Transmission Model (CTM) was introduced by Daganzo with a series of publications during the 90's [1, 2, 3] as a numerical approximation of the shockwave theory. Daganzo's CTM has been created originally for highway implementations. However, due to its simple formulations and high-speed execution, the CTM is considered advantageous for model-based Adaptive Traffic Control Systems (ATCSs). Daganzo [4] introduces the first adaptation of the CTM on signalized roads and Ziliaskopoulos and Lee [5] present the first application of the CTM on signalized intersections. Recently, the CTM appears in publications that deal with the online signal plan optimization in urban networks. Characteristic examples of this trend are the dissertations of Almasri [6], Rohde [7] and Pohlmann [8]. Zeng [9] extends the CTM in order to apply it into an urban network for Sitraffic Motion, which is a state of the art model-based ATCS developed by Siemens AG. Sitraffic Motion uses vertical queuing models to calculate two performance indices in order to optimize the signal plans: the number of stops and the waiting time. However, it is decided to implement a horizontal queuing model in Sitraffic Motion, namely the CTM. The fundamental difference between these two approaches (vertical queuing-horizontal queuing) is that vertical queuing models do not take into account the physical length of the vehicles in the queue; the queue is modelled as a single point with certain capacity (point queue models). On the contrary, horizontal queuing models can model the physical spillback of the queue and therefore are considered to be more realistic (spatial queue models).

The Cell Transmission Model and its extensions for urban networks

The CTM divides the links into discrete segments, known as cells, and updates the density of each cell (number of vehicles) after every calculation interval (typically one second). The length of each cell is selected (by model definition) as the distance traveled by one vehicle in one time interval with free flow speed. Figure 1 illustrates the basic notions of the CTM. It has to be clearly stated that for the CTM cars are not distinguishable within the cells. The colored rectangles (left part of Figure 1) are used to support an intuitive understanding of the model. The right part of Figure 1 illustrates how the CTM decodes the presence of vehicles in a cell. Please note that the number of vehicles in a cell may not be an integer number.

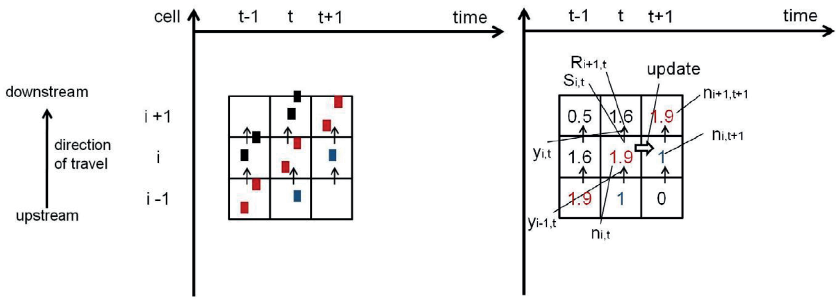


Figure 1: Basic notions of CTM

$n_{i,t}$: number of vehicles in cell i at time t (equivalent to the density of cell i at time t)

$y_{i,t}$: outflow of cell i at time t

$y_{i-1,t}$: outflow of cell i-1 at time t (inflow of cell i at time t)

$S_{i,t}$: sending ability of cell i (upstream) at time t

$R_{i+1,t}$: receiving ability of cell i+1 (downstream) at time t

The simulation in the CTM starts with a given state ($n_{i,t}$) of the cells and follows two simple steps. First the flows ($y_{i,t}, y_{i-1,t}$) between all cells are calculated using Equation (1) and then the number of vehicles ($n_{i,t+1}$) in each cell is updated using Equation (2).

$$y_{i,t} = \min\{S_{i,t}, R_{i+1,t}\} \quad (1)$$

$$n_{i,t+1} = n_{i,t} + y_{i-1,t} - y_{i,t} \quad (2)$$

The flow between two cells (Equation 1) is the minimum between how many vehicles the upstream cell can send ($S_{i,t}$) and how many vehicles the downstream cell can receive ($R_{i+1,t}$). The number of vehicles in cell i at time t+1 ($n_{i,t+1}$) is equal to the number of vehicles in that cell at the previous step ($n_{i,t}$), plus the inflow ($y_{i-1,t}$), minus the outflow ($y_{i,t}$) for that cell during the time interval t. Figure 2 illustrates the simplified trapezoid flow-density relationship that is used by Daganzo's CTM. Daganzo proved that the results of the approximation converge to those of the hydrodynamic model [2].

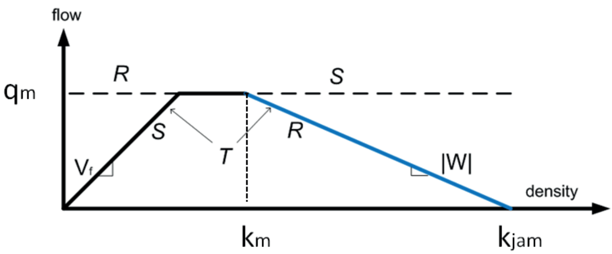


Figure 2: Flow-density relationship of the CTM

V_f : Free-flow speed

q_m : Maximum flow (saturation flow)

k_m : Saturation density

k_{jam} : Maximum density (jam density)

W : Backward shockwave speed (when traffic is congested)

S : Sending ability

R : Receiving ability

T : Function of flow-density ($y = T(k)$)

In order to simulate a whole network, Daganzo used three network topologies to describe road connections: The *Ordinary Links*, the *Merges* and the *Diverges*. Since then, many extensions have been proposed for a better simulation of urban networks, but the fundamental principles of the CTM remain the same (Equations 1 and 2). Zeng [9] developed the Motion-CTM as an implementation of the CTM in Sitraffic Motion (Figure 3). In addition to the ordinary cell connections (*Flow Model*), the Motion-CTM uses some special extensions to connect the links. These extensions are based on the *Merges* (*Merge Model*) and *Diverges* (*Diverge Model*) that Daganzo originally suggested but are proven to be more appropriate for urban applications. Furthermore, the Motion-CTM introduces the so called "virtual cells" (Figure 3). Virtual cells are added at both ends of each link and are used to simulate the connection between the links of the network. In addition, the virtual cells simulate the effect of the traffic lights by blocking the appropriate virtual cell. The virtual cells have no length and are added only for simulation and computational purposes.

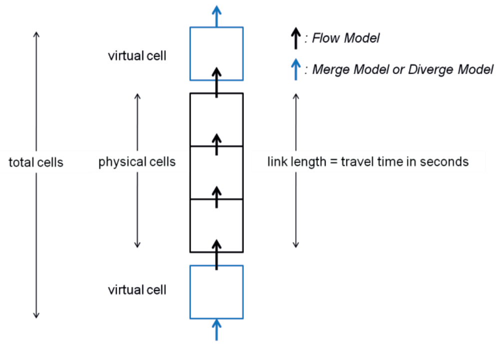


Figure 3: Motion-CTM: Introduction of Virtual Cells

Review of known CTM-based performance indices

Even though various extensions of the CTM have been introduced the last years, only two methods for calculation of CTM-based performance indices can be distinguished: The approximation of the number of stops on a link by Lin [10] and the estimation of the total delay on a link by Almasri [6].

Lin and Wang present in their work [10] a Mixed-Integer Linear Programming formulation based on the CTM and propose an approximation of the number of stops. For the estimation of the stopped vehicles, they use the flows of two consecutive time steps. They show that the number of stops for a link can be approximated with the formula:

$$Number\ of\ Stops_{link} = (0.5) \times \sum_{t} \sum_{i} |y_{i,t} - y_{i-1,t-1}| \qquad (3)$$

In the above formula, $y_{i,t}$ indicates the outflow of cell i at time t and $y_{i-1,t-1}$ indicates the outflow of cell i-1 at time t-1.

Almasri [6] uses the definition of the total delay in cell i originally given by Daganzo [1]. Almasri presents a concrete approach to derive the total delay on a link with the CTM. This approach is also adopted by Pohlmann [8]. For a time interval of one second, the delay ($D_{i,t}$) in one cell during one simulation step is: $D_{i,t} = n_{i,t} - y_{i,t}$ .The total delay on a link that has n number of cells can be estimated by summing up all delays during the examined period:

$$Delay_{link} = \sum_{t} \sum_{i=1}^{n} D_{i,t} = \sum_{t} \sum_{i=1}^{n} (n_{i,t} - y_{i,t}) \quad (4)$$

In the above formula, $y_{i,t}$ indicates the outflow of cell i at time t and $n_{i,t}$ indicates the number of vehicles in cell i at time t. Since the outflow from a cell can never be bigger than the number of vehicles in the cell, the value in the parenthesis is never a negative number: $D_{i,t} = n_{i,t} - y_{i,t} \geq 0$.

Congestion Indicator (CI)

The Extended Motion-CTM [11] introduced algorithmic improvements and new extensions in order to calculate the necessary performance indices for traffic light optimization in Sitraffic Motion. A new cell variable is introduced: the so-called "Congestion Indicator" (CI). This extra variable is added to the cells of the Extended Motion-CTM and is updated in every time step. The main function of the CI, as the name suggests, is to identify which cells are congested. The CI stays active until the congestion dissolves. Furthermore, the CI facilitates the calculation of the number of stops and the waiting time. Additionally, the CI has one more important task in the Extended Motion-CTM. It identifies the source of the congestion. When the CI is active, it gets a value that represents the traffic signal that caused the congestion. Hence, it enables the calculation of signal-related performance indices.

Figure 4 presents an overview of the developed algorithm in the form of a simple finite-state machine. The algorithm for the CI works in three conditional steps: the *Generation*, the *Propagation* and the *Holding*. When the *Generation* condition is true, the CI variable is generated and it takes the value of the signal ID. When the *Propagation* condition is true the CI is propagated to the upstream cells. When the *Holding* condition is true, the CI is kept active for the next update. If the *Holding* condition is not true, the CI is reset to zero.

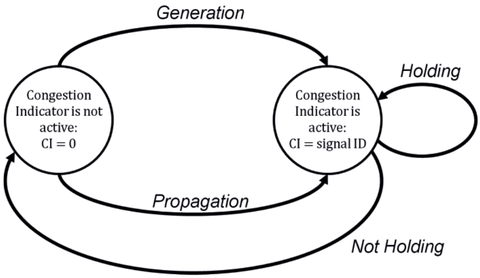


Figure 4: Finite-state machine of the Congestion Indicator algorithm

In terms of a graphical representation as in the shockwave theory, the CI is trying to identify the cells (yellow cells in figure 5) defined by the two shockwave lines as shown in figure 5, by exploiting the calculated densities of the cells in every time step.

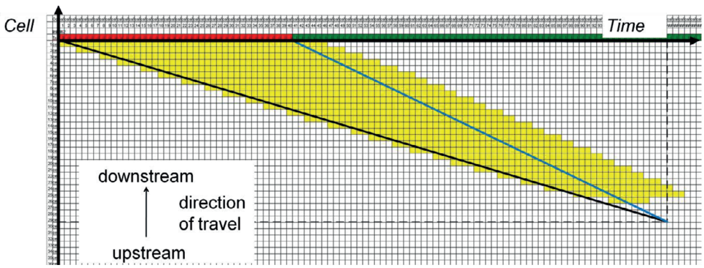
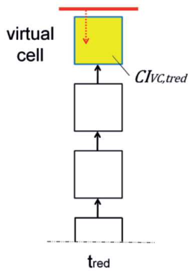


Figure 5: Congestion Indicator: Output of the Extended Motion-CTM and theoretical shockwaves

The following lines describe the algorithm and the aforementioned conditions (Figure 4). The Congestion Indicator algorithms, even though they are developed for Sitraffic Motion, are valid for any potential CTM implementation.

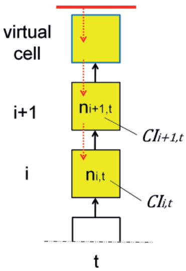
<u>Generation:</u>

This step simulates the start of the congestion caused by the red traffic signal. If the traffic light is red, the CI variable is generated according to the signal ID. The CI is passed to the virtual cell of the link in front of the traffic light.

	*<u>Generation:</u>* if traffic light is red, then, $CI_{VC,tred} = signal\ ID$ else, $CI_{VC,tred} = 0$

Propagation:

This step simulates the propagation of the congestion in space against the traffic flow. If the number of vehicles in a cell ($n_{i,t}$) is bigger than the available space in the downstream cell ($N_{i+1,t} - n_{i+1,t}$), the congestion reaches the examined cell. In that case, the Congestion Indicator ($CI_{i+1,t}$) from the downstream cell is passed to the upstream cell ($CI_{i,t}$). $N_{i+1,t}$ (maximum density of a cell by model definition) is the maximum allowed number of vehicles for the downstream cell.



Propagation:

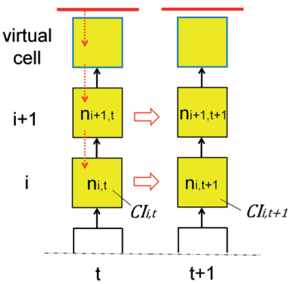
if $n_{i,t} > N_{i+1,t} - n_{i+1,t}$,

then, $CI_{i,t} = CI_{i+1,t}$

else, $CI_{i,t} = 0$

Holding:

This step simulates the duration of the congestion. If a cell has the Congestion Indicator ($CI_{i,t}$), it keeps it as long as the number of vehicles ($n_{i,t}$) in that cell is bigger than the saturation density (k_m).



Holding:

if $CI_{i,t} > 0$

AND $n_{i,t} > k_m$,

then, $CI_{i,t+1} = CI_{i,t}$

else, $CI_{i,t+1} = 0$

Number of stops

The calculation of the number of stops $(NoS_{i,t})$ in a cell i at time t utilizes the Congestion Indicator $(CI_{i,t})$ variable. Complete stops occur only at the end of the queue. In fact, the number of stops in one time interval is equal to the inflow at the end of the queue during that time interval. Consequently, if the end of the queue is identified, the flow of that cell can be derived and accordingly the number of stops. Figure 6 illustrates the result of the algorithm that recognizes the end of the queue cells. The grey cells (both dark grey and light gray cells) represent the end of the queue cells that are included in the $NoS_{i,t}$ calculations. To distinguish between the grey cells, the light grey cells are labelled simply as $EQ_{i,t}$ and the dark grey cells are labelled as $EQ'_{i,t}$. The $EQ'_{i,t}$ cells are distinguished from the $EQ_{i,t}$ cells in order to model the sudden transition (jump) of the end of the queue from a downstream cell (i+1) to the upstream cell i.

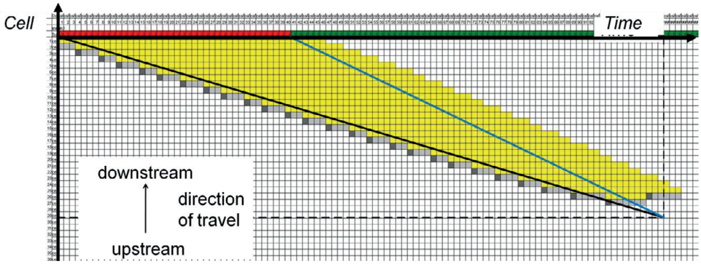
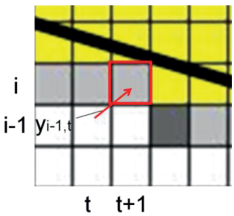
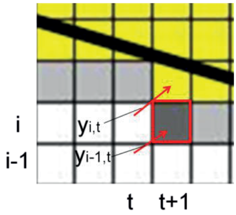


Figure 6: End of the queue cells

After the identification of the cells at the end of the queue is done, the calculation of the number of stops is performed.

<u>*Number of Stops*</u> *$(NoS_{i,t+1})$:*

	<u>*Number of Stops*</u> *$(NoS_{i,t+1})$:* if $EQ_{i,t+1} = active$, then, $NS_{i,t+1} = y_{i-1,t}$



Number of Stops ($NoS_{i,t+1}$):

if $EQ'_{i,t+1} = active$

then, $NS_{i,t+1} = y_{i-1,t} + y_{i,t}$

Based on the above calculations, it is possible to compute the total number of stops in a cell i (NoS_i) for a complete period:

$$NoS_i = \sum_{0}^{t} NoS_{i,t+1}$$

If n is the number of physical cells in one link and m is the number of links of the whole network, the total number of stops in one link (NoS_{link}) and the total number of stops in the whole network($NS_{network}$) are:

$$NoS_{link} = \sum_{i=1}^{n} NoS_i$$

$$NoS_{network} = \sum_{link=1}^{m} NoS_{link}$$

Finally, the number of stops can be assigned to the respective signals, with the help of the CI. Equation (5) gives the total number of stops for each signal in the network:

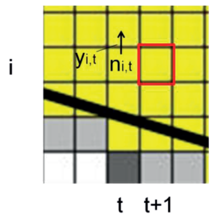
$$NoS_{signal} = \sum_{link=1}^{m} \sum_{i=1}^{n} \sum_{0}^{t} NoS_{i,t+1}^{signal}$$

$$\text{with } NoS_{i,t+1}^{signal} = \begin{cases} NoS_{i,t+1}^{signal}, & if\ CI_{i,t+1} = signal\,ID \\ 0, & otherwise \end{cases} \qquad (5)$$

Waiting time

The calculation of the waiting time ($WT_{i,t}$) in a cell i at time t utilizes again the Congestion Indicator ($CI_{i,t}$) variable. The waiting time is the number of vehicles in the queue multiplied by the time in the queue. In the case of the Extended Motion-CTM (as in the original CTM) the updates happen every second. That means that the waiting time is the number of vehicles that stay in the congested cell and they are not able to leave. Using the notions of CTM this number equals the number of vehicles that are in the cell in the previous time step ($n_{i,t}$) minus the vehicles that are able to leave the cell ($y_{i,t}$). If the vehicles that leave the cell ($y_{i,t}$) is zero, the waiting time in one time interval (1 second) equals the number of vehicles in the cell ($n_{i,t}$).

<u>Waiting Time</u> *($WT_{i,t+1}$):*

	<u>Waiting Time</u> *($WT_{i,t+1}$):* if $CI_{i,t+1} > 0$, then, $WT_{i,t+1} = n_{i,t} - y_{i,t}$

The waiting time ($WT_{i,t+1}$) can never be smaller than zero, since a cell cannot send more vehicles than it has. The total waiting time (WT_i) in a cell (i) is the sum of all waiting times ($WT_{i,t}$) for each time step:

$$WT_i = \sum_{t_{red}}^{t_{blocked}} WT_{i,t+1}$$

The time step when the traffic light turns red is noted as t_{red}. The time step when the Congestion Indicator becomes inactive again (CI is reset to zero) is noted as $t_{blocked}$. This number (WT_i) will grow as long as the cell remains congested, even though the maximum number of vehicles that the cell can hold is limited (N_i). The upper limit depends on how long the cell remains congested (how long the cell keeps the Congestion Indicator active).

If n is the number of physical cells in one link and m is the number of links of the whole network, the total waiting time of the link (WT_{link}) and the total waiting time in the whole network ($WT_{network}$) are:

$$WT_{link} = \sum_{i=1}^{n} WT_i$$

$$WT_{network} = \sum_{link=1}^{m} WT_{link}$$

Finally, the waiting time can be assigned to the respective signals, with the help of the CI. Equation (6) gives the total waiting time for each signal in the network:

$WT_{signal} = \sum_{link=1}^{m} \sum_{i=1}^{n} \sum_{0}^{t_{blocked}} WT_{i,t+1}^{signal}$ $with\, WT_{i,t+1}^{signal} = \begin{cases} WT_{i,t+1}^{signal}, if\, CI_{i,t+1} = signal\, ID \\ 0 \quad , \quad otherwise \end{cases}$	(6)

Evaluation

In order to evaluate the developed algorithms a test network from a city that has implemented the Sitraffic Motion is chosen, the city of Magdeburg. The evaluation compares the proposed methodology with the existing methods. The theoretical point of reference is the shockwave theory, since the CTM is a numerical approximation of the shockwave theory. The selection of the test area is made with the purpose of examining a real world critical area. The test area is part of the main corridor of the city (increased vehicle flows) and contains two signalized intersections that are relatively close (85m) to each other (Figure 7). The evaluation that follows focuses on the corridor from east to west on intersection K452 and especially on links 61 and 62. The fundamental diagram that is applied for the evaluation has a simplified triangular shape.

Figure 8 shows that for all inflows the performance of the new proposed algorithm is clearly better than the existing methodology. One more inherent advantage of the Extended Motion-CTM algorithm is that it has the ability to assign the calculated number of stops to the specific signal that originally caused the congestion and the subsequent stops. Furthermore, the performance of the algorithm is not affected by a potential big inflow that causes oversaturation. This is considered a big advantage of the new proposed formula, since these are the crucial cases for traffic light optimization.

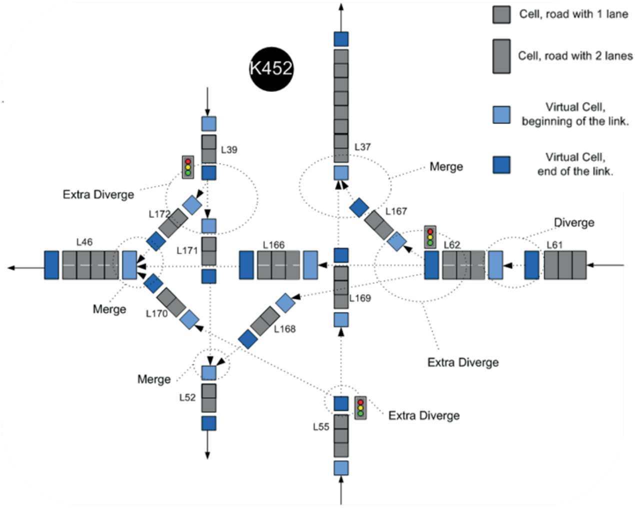


Figure 7: Test Area: Detailed plan of cells

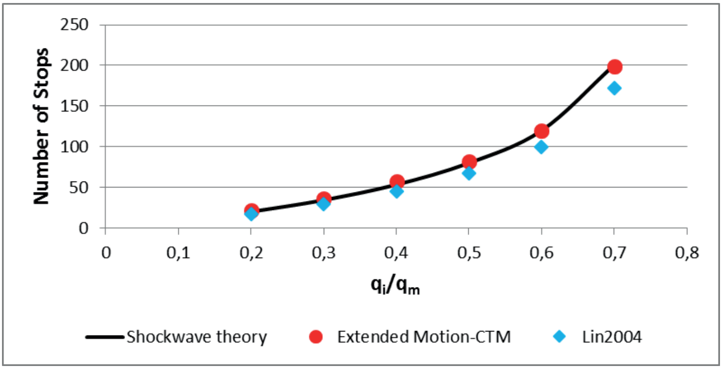


Figure 8: Number of Stops for various inflows

To get a better feeling of the importance of the precision for big inflows, the two extreme cases of Figure 8 can be beneficial. For a ratio of q_i/q_m equal to 0.2, the overestimation by the Extended Motion-CTM is less than two vehicles (1.6840 stopped vehicles). The respective underestimation by the Lin formula is 2.4 stopped vehicles. For the case of oversaturation (ratio of q_i/q_m equal to 0.7) the underestimation by the Extended Motion-CTM is just over two stopped vehicles (2.3514 stopped vehicles). The respective Lin underestimation is almost 30 vehicles (29.0584 stopped vehicles). This difference is solely for one oversaturated intersection. Consequently, this difference, in terms of missed stops, becomes extremely big for larger networks with many oversaturated intersections. Thus, the new algorithm that is proposed in this paper can be considered as very reliable even for big networks and oversaturated conditions.

Figures 9 and 10 give a more detailed look of the performance of the algorithms compared to the theoretical values derived from the shockwave theory for every second during two cycles. The continuous line illustrates the expected values from the shockwave theory. The points in Figure 9 give the results of the algorithm by Lin [10] and the points in Figure 10 give the results of the developed algorithms based on the Congestion Indicator [11].

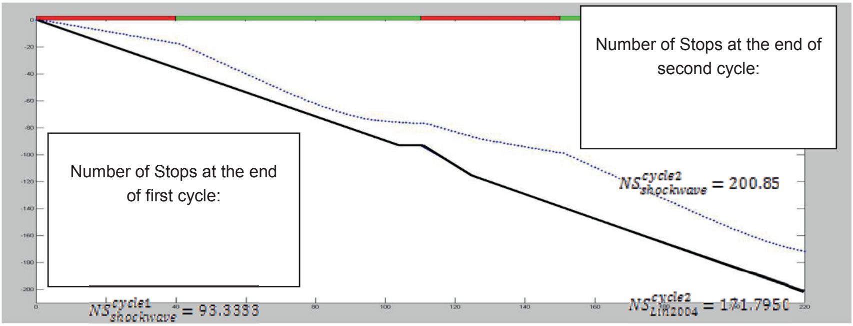


Figure 9: Number of stops comparison: Lin [10] and shockwave theory

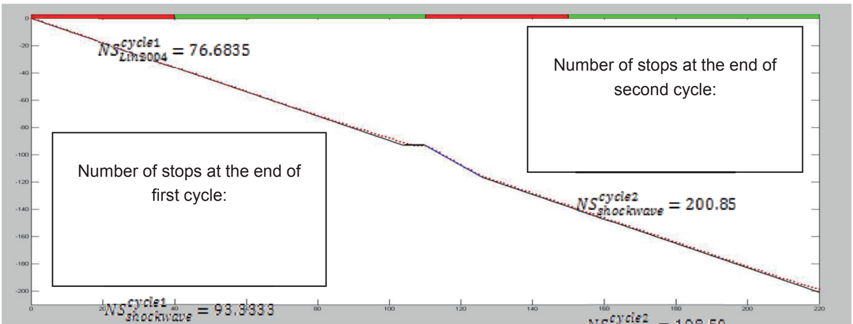


Figure 10: Number of stops comparison: Extended Motion-CTM [11] and shockwave theory

$$NS^{cycle1}_{EMCTM} = 93.2174$$

The evaluation of the waiting time calculation on the same corridor shows that the developed algorithms are very accurate (Table I).

	Waiting time (end of 2nd cycle)				
q_i/q_m	Shockwave theory	Extended Motion-CTM	Almasri2006 (Delay)	Extended Motion-CTM vs. Shockwave theory	Almasri2006 (Delay) Vs Shockwave theory
0.2	400.0000	398.0085	400.0000	- 0.4979 %	0.0000 %
0.4	1066.7000	1062.2129	1066.8000	- 0.4207 %	+ 0.0094 %
0.7 (oversaturation)	4637.5636	4572.7693	4612.4885	- 1.3972 %	- 0.5407 %

Table 1: Waiting time for various inflows

Conclusions

This paper presents a new methodology for the calculation of the number of stops and the waiting time based on the Cell Transmission Model (CTM). With the development of the "Extended Motion-CTM" [11], a new variable for every cell in the network was introduced, the so called "Congestion Indicator" (CI). The CI identifies the congested area defined by the shockwave generation. It is modeled as a state for each cell and is defined using a finite-state machine approach. The CI faciliates the calculation of the number of stops and the waiting time. In addition, the developed methodology allows the association of the calculated values to the responsible traffic signal. The evaluation on a real world critical corridor shows very promising results. However, a complete network evaluation is needed to establish the value of the methodology for online signal plan optimization for urban networks. Comparison with various traffic models (microscopic and macroscopic) is considered to be the next research step.

Acknowledgements

We would like to thank the Institute of Transportation, Technische Universität München and the Research and Development, Intelligent traffic Systems, Siemens AG for making this work possible.

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Part II: Multi-modal Cooperation and Interaction

Agent-based modeling and simulation of individual traffic as an environment for bus schedule simulation

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Abstract

To re-establish the regular driving operations of a tram network, which was disturbed significantly by unforeseen external events, traffic schedulers apply rescheduling and rerouting strategies. These strategies are usually multi-modal; they consider the interaction of trams, buses, even taxis. Thus, to evaluate the applicability of a given rescheduling or rerouting strategy prior to its implementation in the real-world system, a multi-modal simulation software is needed. In this article we present an agent-based model of individual traffic which will be applied as background to a planned simulation of bus traffic. These combined models are to be integrated with an existing tram schedule simulation; the resulting multi-modal model will then be applied to evaluate the usefulness of given rescheduling or rerouting strategies. After a short introduction to agent-based modeling and simulation, as well as to existing models of individual traffic, this paper proposes to model the behavior of individual traffic as an environment for agent-based bus schedule simulation. Finally, some experiments are conducted by modeling and simulating individual traffic in Cologne's highly frequented Barbarossaplatz area.

1 Introduction

In many tram networks multiple lines share tracks and stations, thus requiring robust schedules which prevent inevitable small delays from spreading through the network.

Feasible schedules also have to fulfill various planning requirements originating from political and economic reasons. In [8] and [17], some of the authors present a tool set designed to generate tram schedules optimized for robustness, which also satisfy given sets of planning requirements. These tools are aimed to assist traffic schedulers to compare time tables with respect to their applicability and evaluate them prior to their implementation in the field.

We now want to extend the tool set to consider larger disturbances, e.g. originating from broken down trams, closed stations, or other blocked resources. Careful schedule design is not sufficient to handle these major disturbances, traffic operators have to apply rescheduling and rerouting strategies (see [7] and [9]) to reestablish regular operations. To be effective, these strategies are inevitably multi-modal: trams are rescheduled to compensate for cancellations, buses are rerouted to relieve the tram network, some traffic operators even co-operate with taxi companies (see [18]). To evaluate the applicability of a given rescheduling or rerouting strategy prior to its implementation in the real-world system, a multi-modal simulation software is needed.

This paper presents a first step towards building that simulation engine. To map multi-modal traffic, a model of bus traffic will be incorporated into the existing tram simulation. Buses are highly dependent on surrounding individual traffic, so a valid model has to include at least a coarse representation of its behavior. Because we aim at an agent-based model of multi-modal traffic, individual traffic can be seen as the environment in which buses - modeled as agents - act and interact according to their set of rules and strategies. Central goal of this paper is to present the design and implementation of an agent-based model of individual traffic, to be used as an environmental layer to a bus traffic simulation yet to be developed.

The remainder of this paper begins with a presentation of some background on agent-based modeling and simulation and the simulation of individual traffic (section 2). We continue with presenting a model of individual traffic as an environment for agent-based bus schedule simulation (section 3). Based on an implementation of this model, some experiments are conducted, focusing on Cologne's Barbarossaplatz area, a highly frequented part of Cologne's inner city street network (section 4). The paper closes with a short summary of the lessons learned and some thoughts on future work (section 5).

2 Background

2.1 Agent-based modeling and simulation

Agent-based modeling and simulation (ABMS) is a comparatively new approach of modeling complex systems as sets of autonomous, interacting agents (for this section see [10]). The behavior of the agents is determined by state variables (attributes) and sets of internal rules. The individual agents act on local information and interact with a subset of other agents and the environment they exist in. In many cases, self-organization can be observed, patterns and structures emerge that were not explicitly modeled. The approach has a broad range of applications in various fields of research, including the study of pastoral-nomadic land use systems (see [6]), of the human immune system (see [4]), of the population growth and collapse of ancient civilizations (see [1]), and of public and individual traffic systems (e.g. see [3], [14], and [15]).

An agent-based model usually includes three components: The agents, their interaction rules, and the agents' environment.

The agents are usually self-contained and autonomous; they have attributes whose values change over the course of the simulation run. Their behavior is determined by a set of rules, and they interact dynamically with other agents and the environment they exist in. In more complex models, agents are often goal-directed and adaptive, and may even be heterogeneous.

Because agents interact only with a local subset of other agents, their neighbors, only local information is available to them. The agents that are part of a neighborhood are usually determined by the model's topology, which e.g. might be a (static or dynamic) network, a spatial grid, or an aspatial “soup” model. The members of an agent's neighborhood may change rapidly during the simulation run.

In addition to their communication with their neighbors, agents also interact with their environment. This interaction may only provide basic information, like the position of the agents in a spatial model (e.g. street lanes and crossings in a traffic model). It may also provide detailed information, like the capacity of and the maximum velocity on lanes, or the state of embedded street lights. An agent's environment is often built as a complex simulation model itself, e.g. based on cellular automata (again see [6]).

2.2 Simulation of individual traffic

Several approaches to model individual traffic are known, many of them based on cellular automata (e.g. see [11], [12], and [13]), or based on ABMS (e.g. see [3], [14], and [15]).

In [12], Nagel and Schreckenberg present a model for freeway traffic, based on simple cellular automata. The model utilizes a set of very simple rules: If there is a free lane ahead, each car c_i tries to accelerate up to a certain maximum velocity. If another car c_j is registered ahead, c_i decreases its velocity. For randomization, the car's velocity is decreased with a small probability. Lane-switching and overtaking are not possible in this model; it only maps one single lane. Even with its very simple rule set, the model shows some non-trivial and realistic behavior: Results show that up from a certain traffic density, traffic jams develop without an external cause, moving backwards through the model, very much alike observed real-world behavior. In [13] Nagel, et al. extend this approach to multi-lane traffic.

Based on the Nagel/Schreckenberg approach, Moltenbrey and Bungartz (see [11]) aim at simulating real world situations. Their model includes lane-switching and heterogeneous vehicles, many of them filling more than one node of the cellular grid. Bicycles and motorcycles are included with an unique behavior and are not just modeled as slower cars. Each vehicle follows its individual activity plan: It has a pre-planned route from trip origin to destination, calculated with a shortest-path algorithm. This algorithm considers waiting periods resulting from traffic jams, and dynamically chooses alternative routes. The model also includes public transportation, modeling time tables as special activity plans. Because of all these points, the model is necessarily very complex, and stretches the paradigm of cellular automata.

Several agent-based models (of different complexity) of individual traffic are known, each fitted for its special application.

Ehlert and Rothkrantz propose a multi-agent model (see [3]) of urban individual traffic. Their agents are quite complex and capable of what they call "tactical-level driving". The agents are designed modular; each module takes part in the decision process and can be adapted or replaced. Those modules include a sensor module, memory for storing data, a controller for regulating access to the memory, a short-term planner, multiple sets of behavior rules, and an arbiter which selects the best action proposed by the behavior rules.

Paruchuri, Pullalarevu and Karlapalem (see [14]) present a model targeted at simulating individual traffic in Indian metropolises, which they term as "chaotic". Therefore no traffic lights or global overtaking rules are modeled. They try to map a realistic behavior of different driver types, and therefore include several psychological traits. The driver types have attributes like favorite speed, preferred values of acceleration and deceleration, and individual reaction time. To further enhance the model's behavior, the simulation engine includes a relatively complex model of the involved physics. Among other things, the results show a positive correlation between number of aggressive drivers and average speed.

Seele, et al. (see [15]) describe an agent-based simulation of individual traffic as an environment for a human-in-the-loop bicycle simulation. They are therefore interested in a sufficiently realistic behavior. The agents are required to comply to traffic rules, but should also be able to act irrationally and break those rules, so that human participants can experience a sense of danger. Therefore cognitive processes are modeled, based on psychological personality profiles. This approach yields complex agents which take up a lot of computing power. The agents act and interact in a real time environment, which sets a hard upper limit to acceptable processor time. On the other hand, this allows for a complex model, because the simulator does not aim at an as-fast-as-possible speed, or analytical results obtained by a high number of simulation runs.

3 Modeling individual traffic

Because our model of individual traffic will be applied as a backdrop for a model of time table based bus traffic, and thus cannot use up much processor time, we aim for simplicity. From the perspective of the bus agents to be embedded, the individual traffic's swarm behavior has to be represented accordingly. This means that the behavior of each single agent does not necessary have to be mapped in detail, decision processes can therefore be simplified. For these reasons, the proposed method will be less complex than the techniques shown in section 2.2.

3.1 Modeling lanes and crossings

The street network is modeled as an attributed graph, with directed edges representing lanes, and nodes representing splits, joins, traffic lights and other focal points.

Edges have attributes like length, and up to two neighboring lanes (left and right), which go in parallel. Switching lanes is allowed between direct neighbors, as long as the agents find enough free space on the neighboring lane.

As prescribed by the topology of the observed system, nodes dissect lanes into parts of maximal length. If a lane is dissected by a node, all neighboring lanes also have to be dissected to keep the transitive closure intact.

There are three types of nodes: Intersections, joins, and splits. Intersections are nodes with up to one incoming and up to one outgoing edge, and thus without the opportunity to change direction. Some of these are applied as entry points or exit points of the model. Joins are nodes with more than one incoming lane and one outgoing lane. Splits are nodes with one or more incoming lanes and more than one outgoing lane. Here, it is possible for the vehicle to choose one of the outgoing lanes, based on a given set of probabilities.

Nodes can be blocked when vehicles on incoming lanes have a precedence in the right of way. Some nodes include traffic lights, blocking and freeing access to their outgoing edges. This is accomplished by a basic event-based system (as described in [2]), which administrates the light switching events. Lights switch between phases of red and green, following observed time intervals. The lowest common multiple of these phases is called cycle time t_c. The described event mechanism is also utilized to schedule the generation of new vehicles at certain entry points.

3.2 Modeling vehicles

The neighborhood of each agent is described in a predecessor graph, which maps the relationship between each vehicle and its preceding and succeeding car. Because the predecessor/successor relationship also has to work for two vehicles on different lanes, this graph is not always symmetric. The relationship has to be updated each time a vehicle passes onto another edge, either by moving over a node or by switching the lane. Thus, each agent knows which vehicle constitutes its immediate predecessor, and can therefore adapt its speed according to the current distance and speed of that car.

A vehicle is represented by an agent which includes a set of attributes like speed, position, size, and preferred acceleration and deceleration. The agent's rule set can be discerned in three areas: Accelerating and braking, changing direction, and switching lanes.

Accelerating and braking: For simplicity we assume uniform acceleration for all vehicles. At each step of simulation time, the agent has the opportunity to change its velocity, depending on the current distance d_0 to the agent's predecessor or an upcoming traffic light. If d_0 is greater than a lookahead l_{max}, the obstacle is ignored and the agent accelerates with its preferred value, up to its maximum velocity. If d_0 is less than or equal to the lookahead, and if the obstacle moves faster than the agent, an acceleration value is calculated so the minimum security distance is not violated. If the obstacle has a slower speed than the agent, a deceleration value is calculated so that the minimum distance S_D can be reached and the agent has the same velocity as its predecessor at that point. With v_0 as the agent's velocity,

w_0 as the obstacle's velocity, and *b* as the obstacle's acceleration, the agent's acceleration *a* can be computed as:

$$a = \frac{1}{2} * \frac{(w_0 - v_0)^2}{S_D - d_0} + b$$

To achieve a higher degree of realism, the agent will only initiate a deceleration if *a* is lesser than a deceleration threshold $r_d < 0$. As an example it could be assumed that a driver going at 4 km/h who notices an obstacle 70 meters away, would not immediately brake to reach a velocity of zero at the obstacle. Instead she would probably accelerate for a while and then brake sharper, thus reaching the other car's position in a shorter time.

Changing direction: If an agent gets to a split node it has to choose one of the outgoing edges. To accomplish this in a realistic way, each dissection features a probability table; its values are derived by observing the real-world crossing. There is a small probability of an agent to move in a circle and thus to never leave the model in the course of the simulation run. Though this behavior would not be realistic (or would it?), for our purposes this is negligible: A few non-realistic vehicles would not compromise the resulting swarm behavior.

Switching lanes: An agent tests whether switching a lane would be safe and advantageous. Thus, two conditions, the security condition and the gain condition have to be fulfilled. *Security condition:* An agent can only switch lanes if there is sufficient free space on the target lane. Additionally, the agent can only change its speed up to a given amount v_{change} to match its velocity to the hypothetical successor and predecessor on the target lane. *Gain condition:* A lane-switch is seen as an advantage, if 1) the possible acceleration *a'* on the target lane would be greater than the possible acceleration *a* on the current lane, and 2) the gain of $(a' - a) > 0$ is not counterbalanced by a loss $(b' - b) < 0$ of the successor agent on the target lane. This comparison is balanced by the agent's individual "altruistic factor" τ and a minimal gain parameter $\lambda > 0$, which prevents lane-switching for a minimal gain. Thus, lane-switching is supposed to be advantageous only, if $(a' - a) + \tau * (b' - b) > \lambda$.

4 Experiments

4.1 Modeling Cologne's Barbarossaplatz area

The Barbarossplatz area (see figure 1) is a highly frequented part of Cologne's inner city network. Here the major arteries of Hohenstauffenring/Salierring, Luxemburger Straße/Weyerstraße, and Roonstraße meet; they are joined by minor roads like Mauritiuswall and Kyffhäuserstraße. Barbarossaplatz is also one of the hubs of Cologne's public transport network, so that buses and trams cross the area periodically.

The area was modeled with 88 nodes and 58 lanes of an accumulated length of 6,979 meters (see figure 2 and table 1). There are eight traffic lights, with a traffic light cycle time t_c of 105 seconds. The vehicle numbers at the entry points were measured at a typical workday evening (see table 2), tables of probabilities for direction changing were also derived from observations.

As major simulation parameters we set a maximum velocity v_{max} of 54 kilometers per hour, a maximum speed change for lane-switching v_{change} of 18 kilometers per hour, a maximum lookahead for obstacles l_{max} of 70 meters, and a driver's response time of 0.5 seconds. The application is then run to simulate a time interval of 240 minutes.

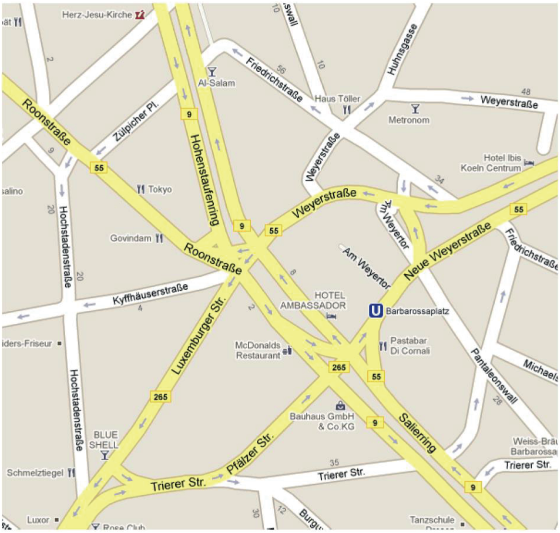

Figure 1: Cologne's Barbarossaplatz area (Source: [5])

4.2 Results and discussion

In the course of a typical simulation run, 18,623 vehicles were generated, they employed an average speed of 19.1 kilometers per hour.

The model's overall behavior seems realistic: The numbers of agents at the entry points are direct results of the simulation parameters and show therefore almost no variations (see table 2). The numbers of leaving agents at the exit points (see table 3) result from the path through the model chosen by individual agents and therefore show some variations. These can be partially explained by the mode of the observation: The numbers of cars at the entry and exit points were gathered sequentially, not simultaneously at all roads.

The simplicity of the model yields some constraints: An agent's path through the model is composed by sequential, independent, and randomized picks without any overriding strategy. Thus, though single decisions are modeled after observations, and therefore match reality, some agents' long-term behavior does not. While the lane-switching behavior seems plausible, it also clearly shows a missing strategy. Agents can be observed to switch lanes in front of traffic lights even if the queue at their current lane is shorter than the one at the target lane, if the predecessor on the target lane is still moving and the one at the current lane is not.

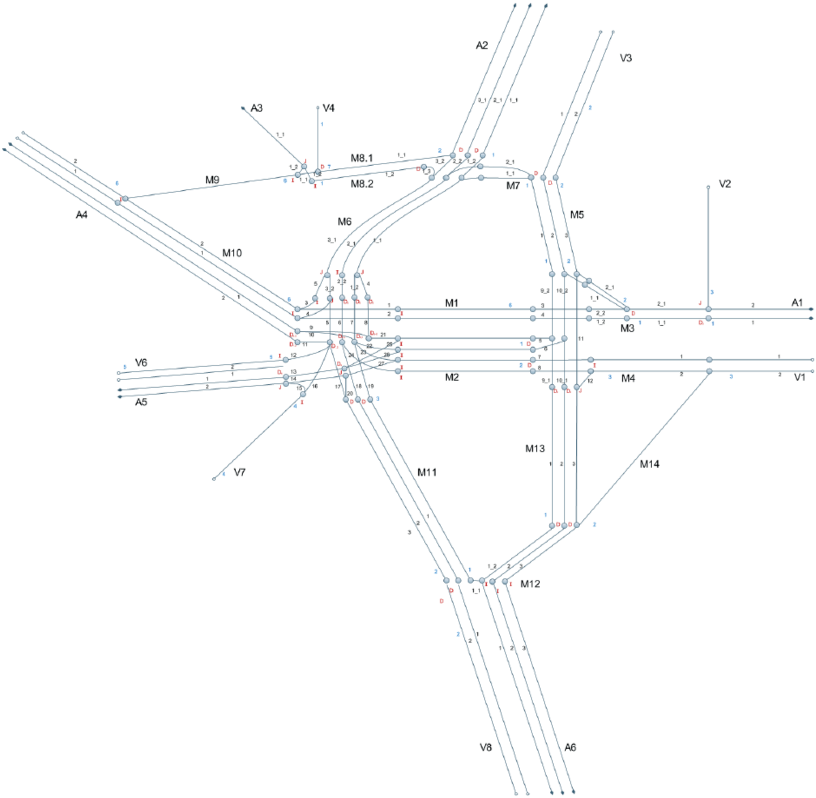

Figure 2: Traffic lane model of the Barbarossaplatz area

No.	N/O Lanes	Lengths
A1	2	12
A2	3	230
A3	1	120
A4	2	170
A5	2	160
A6	3	200
V1	2	150
V2	1	100
V3	2	150
V4	1	60
V5	2	50
V6	2	160
V7	1	160
V8	2	200

No.	N/O Lanes	Lengths
M1	2	100
M2	4	110
M3	2	90
M4	2	90
M5	3	70
M6	3	120
M7	2	55
M8	1	105
M9	1	110
M10	2	120
M11	3	140
M12	3	55
M13	3	95
M14	1	140

Table 1: Number and lengths of lanes

Entry points		Cars per second	
No.	**Name**	**Observed**	**Simulated**
A1	Salierring	0.18	0.16
A2	Neue Weyerstraße	0.50	0.48
A3	Weyerstraße	0.04	0.05
A4	Hohenstaufenring	0.23	0.20
A5	Roonstraße	0.18	0.19
A6	Luxemburger Straße	0.19	0.17
Total		1.32	1.29

Table 2: Numbers of observed and simulated cars at entry points

Exit points		Cars per second	
No.	**Name**	**Observed**	**Simulated**
V1	Salierring	0.15	0.19
V2	Pantaleonsmühlengasse	0.00	0.00
V3	Neue Weyerstraße	0.40	0.40
V4	Mauritiuswall	0.01	0.01
V5	Hohenstaufenring	0.15	0.14
V6	Roonstraße	0.18	0.11
V7	Kyffhäuserstraße	0.02	0.03
V8	Luxemburger Straße	0.36	0.39
Total		1.27	1.28

Table 3: Numbers of observed and simulated cars at exit points

5 Summary and further research

This article presents an approach to model and simulate individual traffic as an environmental layer for the simulation of time table based public bus systems. Following an introduction to the goals and context of our work, it presents some background of ABMS in general and the modeling of individual traffic in particular. We then demonstrate our modeling approach and apply it to Cologne's Barbarossaplatz area.

As a further step of our research, we will develop an agent-based representation of time table based bus traffic which utilizes the proposed model as a background. The combined models will then be embedded with the already existing model of tram traffic (described in [16]) into a common simulation application. This multi-modal application will then be utilized to represent our hometown Cologne's public transportation system.

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The “virtual companion” – User and provider expectations towards mobility assistance for elderly persons

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Abstract

The goal of the project “virtual companion” (Virtueller Begleiter) is to develop and test an “assistant” service that assists in particular elderly people in accomplishing everyday mobility needs. The concept *combines* a *mobile communication* device with remote, but *personal assistance* provided by a specialised call centre. The aim is to keep the handling of the device as simple as possible through a personalised set-up of the device and by transferring the necessary interactions to a voice-based dialogue with the call centre. Target user groups are people with cognitive impairments such as early stages of dementia, but also users who feel uncomfortable when moving around by public transport after a long life as a car driver. The core service offered will be personalised, barrier-free navigation for journeys on foot and by public transport. The device also directs the user inside public buildings, such as U-Bahn stations. This range of functions requires the use of data from different sources, a high level of accuracy in the navigation process and new solutions for routing algorithms. The second key challenge is the development of user interfaces that allow efficient communication. Questions of user acceptance and the insertion of the envisaged service into different service provider settings are equally important. The paper presents the results of the empirical work on user needs, initial reactions to the concept and the institutional setup in the health care, nursing and mobility service sectors.

1 The “Virtual Companion” in a setting of growing needs and shrinking resources for mobility assistance

Mobility is part of everyday life also for elderly citizens, but to move around becomes a more and more demanding task with rising age. Personal mobility is therefore gradually reduced, due to a variety of reasons: Older people suffer from age and health-related mobility impairments, but also cognitive limitations such as visual and hearing difficulties, problems of orientation and dementia. Social and psychological factors such as loss of confidence and interest in the outside world and perceived security contribute as well. Often many of these reasons occur in parallel with a mutually reinforcing effect.

To lead an independent life is nevertheless of prime importance for most senior citizens. This includes the possibility to look after themselves, take care of personal appointments, maintain social contacts and - as necessary part of this - to accomplish the necessary trips, if possible without personal assistance. The loss of these capabilities is often perceived as a fundamental restriction and change, expressed in statements like “If I can’t get out (drive my car, make my way to the bus stop) anymore, then I’m really old”.

A range of options is available in principle for persons in need of assistance for their daily mobility – help from friends and family members, charities and professional nursing and care services, to name just the most important ones. However, the choices available for a specific journey are usually more limited. Furthermore, most forms of assistance are linked to conditions like temporal and spatial availability, costs, formal eligibility criteria, which restrict their usability.

The number of people facing this situation will grow significantly in the coming years as a result of the so-called demographic change. The share of elderly persons suffering most from the limitations described above will rise most (figure 1). As the share of people in the medium age group, the main potential care-givers and travel companions, will decline, the gap between demand and supply will increase [19].

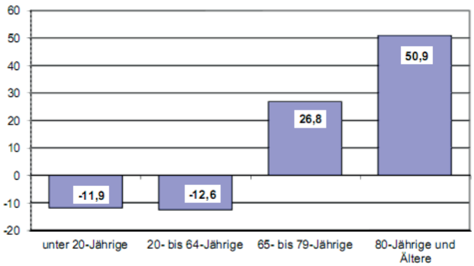

Figure 1: Development of age groups in the German population – percentage change between 2010 and 2030 [4].

This problem can be addressed in several ways. One key approach is to improve and extend the *elderly persons’ capability to lead an independent life* also in old age. A second objective is to *use the available resources* for caring and assistance better. In both cases, technical aids play a major role, even though technology can never replace human contact completely in the social sector.

Based on these considerations, the German Federal Department for Education and Research (Bundesministerium für Bildung und Forschung, BMBF) launched a call for proposals in early 2011 to develop “Seamless mobility chains to overcome, remove or avoid barriers for persons of old age”[10]. As part of this initiative, the R+D project “Virtual Companion” (ViCo, Virtueller Begleiter, ViBe) responds to these challenges.[11] The “Virtual

[10] Official title “Mobil bis ins hohe Alter - Nahtlose Mobilitätsketten zur Beseitigung, Umgehung und Überwindung von Barrieren“, see http://www.mtidw.de/ueberblick-bekanntmachungen/mobil-bis-ins-hohe-alter

[11] Project consortium: DResearch Digital Media Systems (coordination), VIOM digital maps and geo services, Sympalog Voice Solutions, HFC Human-Factors-Consult, nexus Institut, Geriatrics department of Charité Universitätsmedizin Berlin. Associated partners: Verkehrsverbund (public transport authority) Berlin-Brandenburg, Paritätischer Wohlfahrtsverband, Ev. Johannesstift Berlin

Companion” is conceptualised as a technological and operational innovation aiming (a) to allow elderly users with mobility impairments to get support while still pursuing an independent life, and (b) to use the human resources of mobility assistance providers more efficiently. In essence, the “Virtual Companion” shall provide a *personalised navigation and route planning* service based on mobile communication, combined with the possibility to obtain *personal assistance by phone* at any moment. The ViCo of course cannot replace physical assistance like getting on board a vehicle or climbing stairs (see section 3 for further details).

This basic idea raises several questions, which are addressed in the ongoing project. The present paper gives an overview of these issues, focusing in sections 4 and 5 on the attitudes of potential (end) user groups and the potential business and operational models for a “ViCo service”. This is based on the exploratory interviews conducted so far with the different groups. Before this, section 2 outlines the main research findings on elderly persons’ mobility needs, and section 3 provides an overview of the ViCo concept and the technology development issues. Section 6 provides a discussion and an outline of the next questions to be addressed.

2 Mobility in old age

Mobility patterns

Generally, old age is linked with a decrease in personal mobility. The absence of the main mobility cause – commuting to and from workplace – is not compensated by leisure mobility. However, future cohorts of seniors are expected to increase their leisure mobility thanks to their superior physical condition, compared with previous generations. The reduction of trips and the shrinking radius of action that typically evolve with physical complaints of very old age will be postponed to start at the age of 80 or later. In addition to the extension of the period of active living, cultural change means that future seniors will not suddenly abandon their current intense, individual and highly mobile lifestyles as soon as they retire.

As a part of the requirement analysis for the “Virtual Companion” twenty interviews with seniors between 64 and 89 years were conducted and among other things the purposes of their mobility were analyzed. The findings clearly show that the majority of trips are linked to household care and everyday personal matters (cf. figure 2). Even if some gender differences occurred with regard to several mobility purposes, the general level of participation in transportation is the same among both women and men. Shopping is confirmed to be the main reason for mobility by relevant up to date studies, too.

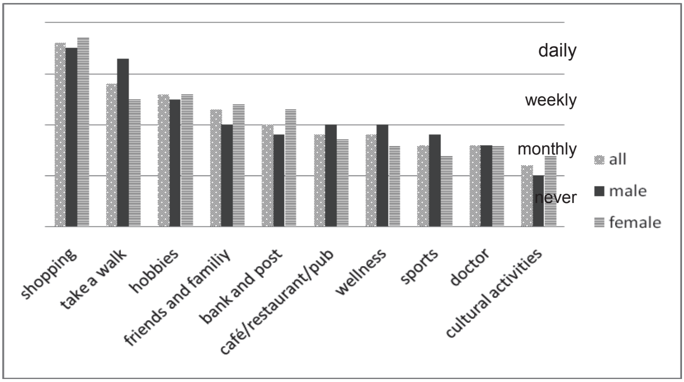

Figure 2: Reasons for mobility, data from ViCo interviews

With regard to their mobility behavior, the (non)existence of a partnership emerges as a major background factor. Elderly living alone expressed wishes to expand their individual activities significantly more often than seniors living together with partners (figure 3). Two interviewees explicitly said “they would like to go for a walk or to a cafe, however not solely”. These insights suggest a higher mobility of seniors living in partnerships, which at first glance seems to be supported by the data – they undertake more trips. However, these seniors are also significantly younger – 75 years on average. Hence, the observed variations regarding higher levels of mobility are probably rather associated with age differences. But partners can also prevent people from being mobile, for example when they take over out-of-home duties or demonstrate no interest in getting out.

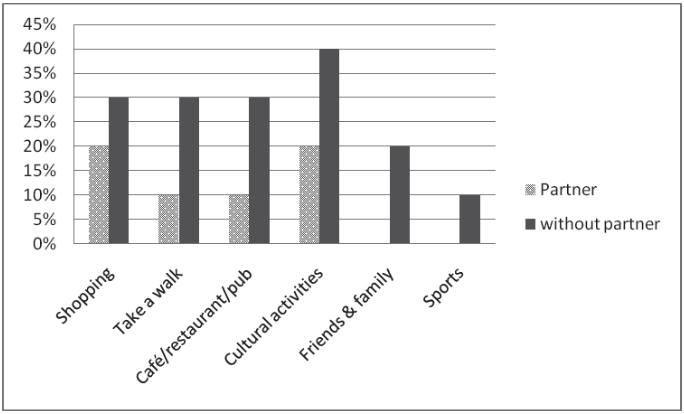

Figure 3: Desire for more mobility, data from ViCo interviews

Modes of transport

It is expected that the already existing dominance of driving a *car* as a mode choice in old age [24] will increase further on. Almost all seniors will have a driver's license and many years of driving experience; plus the currently existing gender differences [10] are likely to be leveled. So far, car usage of the older generation not only prolonged in their lifetime, but also increased overall [24] probably because older people especially appreciate the car that stands for comfort, speed and individuality [3]. Ownership and usage of cars also have important emotional aspects for seniors: According to a survey by the German transport safety council [6] independence is of particular importance for 93 percent of older car drivers. This appreciation of car driving becomes a symbol of independence for some people, which makes it difficult to voluntarily give up driving when it becomes problematic.

Public transportation can help to compensate skill limits and to stay mobile. However, only few of the elderly people make use of this option ([16], p.76seq). There is a small increase in use of the public transportation system amongst elderly people ([15], p.59), but in total it is less used by elderly people as the potential use for elderly people would suggest [3,13]. Only 6 respectively 11 percent of all trips by pensioners at the age of 65-74 respectively 74 years and older are done by public transportation. The public transportation system is not attractive due to several factors:

- The use of buses and trains needs a relatively good mobility, which decreases especially in old years.
- Station platforms are often unreachable barrier-free and during the ride a certain amount of physical strength is needed to grab hold during sharp decelerations.
- The public transport system is personally felt insecure in opposition to the objective security.

In addition ticket machines are often seen by people who do not use them regularly (not only by elderly people) as technical barriers which prevent the use ([25], p.264).

In a case study where old car users where questioned which requirements they expect from public transportation in order to take public transportation more into account for their own mobility, besides the price and security a lack of orientation service was described most detailed: The lack of oversight and comprehensibility, the lack of electronic Train announcements (at trams), the lack of information walls and the lack of help for orientation were criticized. The criticism of the old drivers was confirmed in observational research. Existing technical tools for orientation were confusing and were unable to fulfill their planned use [1,2].

The most important mode of transportation for elderly people are their own feet. Up to 80 percent of people aging 60 and above are daily or at least often on walks. From the 75. year on the percentage of people walking everyday declines, but even of the 85 year old and older 63 percent walk daily or at least often. At the same time the share of walks compared to other modes of transportation increase [7,15,22].The use of bicycles by elderly people has increased as well over the recent decades.

3 Idea and technological challenges of the "Virtual Companion"

Envisaged use cases

The "Virtual Companion" aims at providing assistance in directing the user to his or her destination on trips undertaken on foot and/or by public transport. In addition to arriving at the destination, it is important to showing the way back home as well, especially for persons who are beginning to suffer from dementia. Through the possibility to communicate with the "companion" during the journey, assistance in cases of loss of orientation, change of travel plans or unforeseen service disruptions and of course emergencies shall be provided. The "virtual companion" at the service desk will be able to call assistance for help on the spot, for example caring services, taxis or family members. Further practical assistance and medical surveillance are possible extensions of the concept.

The concept is based on the assumption that the targeted user groups do not use their car anymore.[12] However, many of them will have from their previous lives much more experience as car users than public transport passengers. The change to the unfamiliar public transport environment with the associated loss of direct influence, different ways of orientation and mixing with other people is often a source of stress [9,11,12,17]. If journeys are not made as a result, this will lead to social exclusion [5,14] and loss of patronage for public transport. By providing assistance from "behind the scenes", the ViCo aims to help its users to gain confidence and maintain their independent mobility.

The navigation to be provided will thus focus on the pedestrians' and passengers' perspective. The information required is different from that provided in current navigation systems in that a high level of detail for "small-scale", local journeys is required. This refers for example to the location and nature of steps, ramps, rest facilities and the layout of public transport stations.

Approach

As indicated by the name of the project, the assistance device to be developed in the project should provide a "companion" in the literal sense of the word - a real human being, but instead of being present physically, this person will provide "virtual" company through a telephone and data connection with the user.

The key characteristics and novelties of the concept are

- the conceptualisation of the ViCo service as an integral combination of the *device* held by the user and the assistance provided by the *service desk*
- a far-reaching simplification of the interactions between user and the ViCo device, including the elimination of handling errors

[12] In old age, driving is often perceived as stressful due to age-related impairments (cf. section 2), and hence much reduced [18,20,21]. Apart from that, navigation for car users differs substantially from that for pedestrians, and would have been beyond the scope of the project.

Thanks to technological progress, the ViCo test device will use a standard smartphone as a hardware base. This type of device is useful mainly for the large screen, allowing large-size text displays and graphics to be displayed. However, to address the envisaged user groups - whose experience and affinity to such devices is low or even inexistent - the aim is to develop an user interface that reduces the complexity of such phones to the lowest possible level by

- providing as part of the ViCo service *contract* a personalised setup of the hardware regarding for example preferred font sizes, contrast, destinations and personal contacts
- reducing the functionalities available, and thus the decisions and actions required from the user
- compensating for these (intentional) limitations with the personal assistance offered by the ViCo service desk personnel
- offering voice-based commands as a complement or alternative to interaction via keys or touchscreen

In essence, the system will guide the user by means of pre-defined, personalised procedures. If these are insufficient, the ViCo *service desk* (more precisely: the *service assistants* working there) will take over many of those tasks more adept users of mobile communication can do themselves. The “service assistant” working in the background is therefore a key part of the concept. The assistant can compensate for the limitations and difficulties of automated communication. The fact that a real assistant can be reached at any time is intended as a key characteristic and advantage, in particular with regard to creating trust in the service and acceptance - and hence indirectly confidence of the user in maintaining their independent mobility.

The ViCo concept furthermore envisages possibilities to adjust the service to the user’s needs and capabilities, for example by establishing criteria for assistance, ways of communication, critical events etc. In this way, differing requirements for assistance and different levels of confidence can be accommodated. The service should also be able to be adjusted to different service providers’ environments, which allows the ViCo to be operated in various settings (cf. section 5).

Technological issues and challenges

The concept of the “Virtual Companion” as described above poses several technical challenges, which result from the demands of the user groups/use cases, the envisaged type of communication and the data requirements associated with the service. The system architecture as currently planned is shown in figure 4. The end users (persons accomplishing their mobility with the assistance of the ViCo device) have a contract with a service provider who provides the service desk and employs the assistants (cf. section 5). The service provider in turn uses the routing and voice response facilities provided as part of the overall ViCo server, where the user and service data are also held.

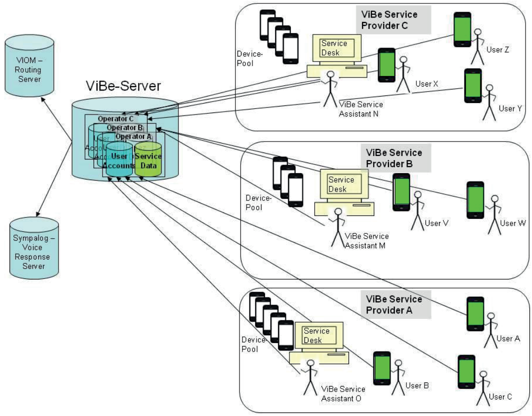

Figure 4: ViCo client-server architecture (source: DResearch) - Note: "ViCo" here shown as "ViBe"

To offer a navigation service for the target group of elderly persons may seem a not too complicated task. After all, this group is characterised by more limited mobility needs if compared to the travel patterns of people in working age or education for which such services are nowadays commonplace. However, several new issues have to be solved for providing this type of navigation:

- Itineraries have to be defined and disaggregated to a much "smaller" level of detail that considers each section and the items segregating them separately (for instance walking distance and direction on platform, lift, walking distance and direction on mezzanine level, position to be taken on new platform).
- Data availability for this information is limited and often missing even in conurbations like Berlin where an advanced level of online travel information for public transport journeys is available. Generally speaking, data on public transport and journeys on foot need to be brought together from different sources, raising issues of compatibility and reliability.
- The system must "understand" the user's wishes even when these are not always formulated precisely or pronounced in the correct way. Although the (human) service assistant will be available to help, it is desirable to resolve "easy" issues between the user and the system without the assistant's involvement. Figure5 illustrates some of the ways in which a user might express a request for a travel itinerary.

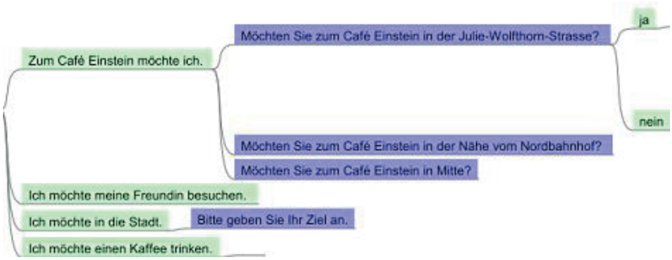

Figure 5: Exemplary start of dialogue requesting a travel itinerary (source: HFC)

- Communication between user, service assistant and server needs to be possible at all times. To make precise and correct suggestions, the system must be able to locate the user also inside of stations and buildings and identify the direction into which he or she is moving.
- A large number of travel options with different characteristics can be produced by the system and presented to the user. Some of them may wish to decide themselves which to choose, but a more often a selection will have to be made by the system (either automatically or by the service assistant). Sufficiently precise descriptions of the user’s profile and suitable parameters for the itineraries need to be established.
- Different expectations regarding privacy and control have to be accommodated in the design of the system (cf. sections 4+5).

4 Who uses the “Virtual Companion”? - Potential users’ expectations and needs

Acceptance

The Virtual Companion is technical tool which supports mobility by foot and the combination of walking and using public transportation the best way possible. In our interviews the interviewed persons report that they are in fear of doing their everyday ways because they have to quit driving due to diseases. Many of them then let relatives drive them around by car. The possibility to drive with somebody will decrease in the future due to demographic transition. To secure somebody’s own mobility after quitting to drive, and to reach destinations beyond walking distance, using public buses and trains is the best option.

However, to get along with public transport can sometimes be difficult even for regular users. Especially the orientation in large stations, where underground, trains, trams and buses intersect is reported to be difficult. The questioned persons report stress when they do not find the right underground entrance or bus stop. The orientation after leaving the stations can cause problems as well. On which side of the street and in which direction the way continues is not always clear at unknown stations.

The intelligent support to overcome these traffic situations offered by the ViCo led us to expect that the questioned pensioners will support the ViCo-concept. However, these expectations were only met partly. 12 out of 20 liked the idea, 8 refused it. Several said that they would like to use the device themselves.

Some of the questioned see that ViCo can support the participation in public life. For example an 82-year old stated that she would be outside more often with the help of the device, as she would not be in fear of getting lost anymore. Another 83-year old stated that she would be more mobile with ViCo as it would simplify many things. Some of the interviewees took voice for even older persons. They stated acceptance for the idea but didn't see themselves as users, but more "others" affected by illnesses or suffering of dementia.

The acceptance of the ViCo Concept was with 6 yes to 3 no votes much higher among persons affiliated to technology than at non-affiliated persons where the acceptance was almost equal (6 yes, 5 no). Interesting to note is that 3 persons who have used GPS navigation devices for journeys car found it "awesome" but refused the same technology to go by foot. They said it would be "distracting" and leading to "overdependence from technology".

Requests to the system

The requirements for the system were developed at workshops with different groups of pensioners. In total the requirements of the pensioners can be reflected in 3 topics (fig. 6). In the basic function *navigation,* the following were the crucial points:

- Reliable information about barrier-free routes, with a distinction between elevators and escalators.
- Data updates not only about routes, but also for barrier-free routes. If the elevators are broken it should be visible in ViCo and it should propose an alternative route, according to the questioned pensioners.
- For connections which are too complicated and too long, a taxi call feature should be implemented.
- Another important expansion function is to show the way to public toilettes if needed.

The ability to route outdoor as well as indoors was a great self-evidence for the workshop participants.

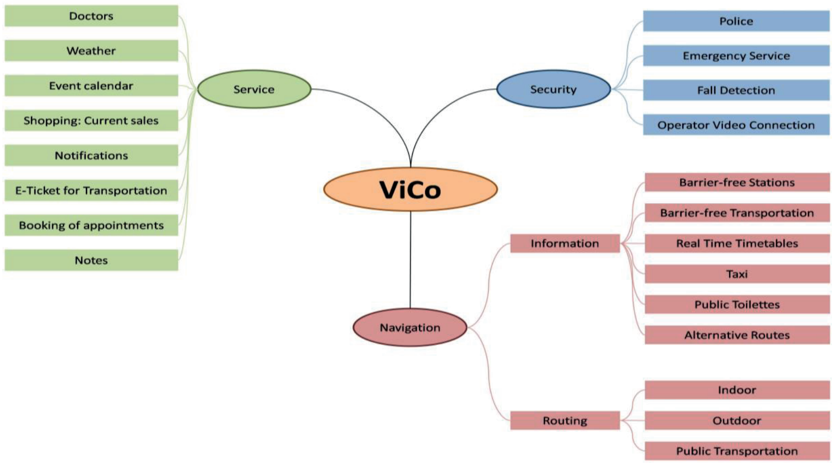

Figure 6: 3 main topics for the ViCo development

The second basic function appears to be the *security*. The ability to call the police or emergency service with the device makes it attractive for pensioners who often feel insecure in public transportation or during the nighttimes. The backup function of the operator was another highlighted and supported feature.

During the workshops a lot of alternative *service features*, often descending from the possible destinations, have been discussed, however many of these functions are in contrast to the aim of ViCo being simple and easy to handle.

The discussed features ranged from Doctor lists to Weather reports and individual event calendars. For these features there are already apps existing, but not in use among the surveyed seniors or the workshop participants, as the use of smartphones not (yet) widespread among the target group.

5 Who provides the “Virtual Companion”? Potential business models and operational concepts

Conceptual issues

To develop the “Virtual Companion” it is necessary to look not only at the technological tasks but also examine how the service could look like in practice. The very nature of the ViCo as an offer combining technical and personal elements makes the question who might provide (operate) this under which circumstances the more important. Linked to this is the question which value propositions and business models are pursued by the potential providers.

The two issues - operational concepts and business models - have a somewhat different focus, but also significant overlap and shall therefore be discussed together in this section. “*Operational concepts*” points at the way in which the various tasks associated with the ViCo service are distributed among the participating institutions, how the activities are coordinated and what kind of resources are employed. The term “*business models*” shifts the focus to user benefits, potential revenue streams and value propositions, hence at the economic dimension (for further terminological overviews see [8,23]. Taken together, the question is who collaborates with whom at which conditions to deliver the ViCo service.

Business and operational concepts in this field need to consider the following characteristics:

- The ViCo service needs resources from different contributors (figure 1, table 1), each with its own interests. The question “what’s it good for?” therefore needs to be answered both for the service as a whole and for the various contributors.
- The “value” created by the service is mainly immaterial (in the form of confidence, self-esteem etc.) and thus difficult to quantify.
- The “value” created is not only assessed by the end user (the person using the ViCo device). Family members and perhaps nursing institutions have a say here as well and may actually be crucial in convincing the end user to take advantage of the service.
- The service is set at the interface of several business sectors (nursing, personal care, public transport) traditionally dominated by public and non-for-profit organisations who do not necessarily follow the commercial logic of market-driven companies

An overview of the main stakeholders to be considered in this concept development is provided in table 1. Due to space limitations, the following discussion focuses on the “service providers” (central column)

	Providers of service components	*ViCo service providers*	*Users*
role	provide hard- or software components or background services	provide assistance and navigation services, run service desk and employ service assistants	persons using the service (holders of the service contract)
examples	data suppliers server providers voice response server mobile phone producers	charities transport providers mobility assistance services nursing homes	elderly citizens, their relatives or legal representatives

Table 1: Main stakeholders/suppliers (source: authors)

Furthermore, the concept of the ViCo is on the one hand new and needs to find its place in the mobility assistance market; on the other hand it competes with several “products” and services like personal mobility assistance, public transport travel information and home emergency call services. The functionalities offered by the ViCo overlap with these without being identical, and the ViCo might be seen as competing, but also as complementary to the present alternatives.

The project work therefore covers not only potential use cases (considering real-life scenarios in which the ViCo might be used), but also research into possible business and operating models. The following paragraphs sum up the results of a series of 18 expert interviews with practitioners involved in providing related services (nursing home and care service providers, charities, assistance providers and public transport operators, each group being represented between 2 and 6 times, some experts being involved in more than one field). The interviews covered two main areas:

1. assistance *services* currently *provided*, resources used, organisational setup and practical experiences
2. *feedback on the ViCo concept*, possible user groups and expectations from a potential provider’s point of view

Empirical results

The interviews show first of all that current mobility assistance services are closely linked to personal help during the trip. The various services are based on the principle of one, sometimes even two, assistants accompanying an elderly or disabled person who would not be able to make the trip alone. Accordingly, these services are almost exclusively used by people requiring a personal assistant – the cognitive and psychological limitations addressed by the ViCo may be present as well, but not on their own. The type of assistance provided is, however, of fairly elementary character (not requiring medical or nursing skills). The assistants are often recruited in social labour or public employment schemes and taken from the pool of long-term unemployed people. They get practical training on how to use public transport, communication skills and essentials on the handling of wheelchairs etc.

There were some interesting differences in the way the providers define their role and the rules they apply to what their staff can and cannot provide. But there was far-reaching agreement on the importance of trust and mutual respect, a precise description of the client’s needs and word-of-mouth as a way to win new users. The assistants must stay calm and reassuring and able to identify critical situations.

Apart from their disability, typical service users can be characterised by living alone, female, age mainly 70 and older. Although a purely qualitative assessment by the interviewees, they were also described as rarely undertaking trips not making use of the service and low affinity to modern communication technologies. It became clear that for many users, the accompanied trip is one of very few possibilities to leave their home and have social contacts.

From these observations, the ViCo appears not to be a meaningful alternative to the personal assistance. But can it be a complement? The responses indicate that this may indeed be the case, but to find users for the service seems not to be easy. The opinion was widely held that the ViCo would not be accepted by the really elderly citizens, who were described as without sufficient technological experience and lack of learning capabilities. Vice versa, many of the “younger” silver agers have enough experience with mobile phones and would not need a special device. Further limitations lie in the limited financial resources of many elderly users of today’s assistance services. However, it was suggested to look at tourists and people with minor mental disabilities as alternative potential user groups, and to see the ViCo less as an “aide” for persons in need and more as a comfort feature.

Considering this, it may not be surprising that the suggestions on the detailed design and functions of the ViCo also differed widely. There was agreement that “security” functions like an emergency call was essential to build confidence with users. The fact that the "companion" would know the whereabouts of the user and can be contacted at any time was also seen as useful and potentially motivating wary persons to dare trips on their own. Beyond this, a wide range of "service functions" was suggested, of which the navigation and public transport information was just one. However, other comments were sceptical of offering a wide range of such options, as this would divert from the aspired simplicity.

The responses also made it clear that the ViCo service could not be directly integrated into the organisations' current working environment. In addition to staff training and allocation of resources to the "companions", procedures for handling requests would need to be defined, including external assistance where necessary. Two basic options emerged: some respondents saw the ViCo better placed in a call centre or home emergency call office, where economies of scale could be used. Others would prefer to manage the service locally, for instance on the level of their nursing home, in order to keep the personal link between users and "companions" and as a special feature and competitive advantage of their institution.

Future business models must therefore consider – provided that a benefit in terms of mobilisation, independence etc. for the end users can be shown – if and how the ViCo could be (part)funded from the Health Services as an officially recognised nursing tool.

6 Discussion and outlook

The project work is characterised by an iterative process of refining the basic idea of the ViCo and develop the necessary technological and organisational solutions. So far (at about 40 % of the project time), a large variety of possible use cases, numerous technical tasks and several ways of implementation have been identified. The challenge now is to narrow these down to the most realistic and promising settings. From the empirical work described above, three scenarios (table 2) seem to emerge.

The coming months will see further work to validate and refine these scenarios as well as further studies into the implications of the different operational models. Further empirical work will focus on the role of family members and on testing the developed device.

Title	*Confidence in public transport*	*Orientation and reassurance*	*Smart tool for active life*
Main target group	former car users without public transport experience	persons with early stages of dementia or orientation difficulties	silver agers interested in exploring new areas
Main motivation for ViCo use	assistance for using public transport	getting back home, personal contact	information and advice for their activities
Typical use case (situation of use)	everyday tasks, inherited activities	short-distance trips	leisure activities, large geographical area
Most likely provider	transport companies	emergency call providers	commercial providers, transport companies

Table 2: Tentative ViCo scenarios (source: authors)

Acknowledgements

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A Priority System for Multi Modal Traffic Signal Control

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Abstract

There are many users of signalized traffic intersections including passenger vehicles, commercial vehicles/trucks, pedestrians, bicycles, transit buses, light rail vehicles, snowplows, and emergency vehicles such as fire trucks and ambulances. North American approaches to traffic signal control are centered on general vehicles with either accommodations for other modes or exceptions for special considerations such as emergency vehicles. This paper presents a unified decision framework for multi-modal traffic signal control that simultaneously considers the needs of different modal users using wireless communications, as well as traditional detection methods. This framework is based on a mathematical optimization model where each modal traveler can request service using priority requests. The mathematical programming framework allows multiple priority requests to be considered simultaneously based on a hierarchical control policy. In addition to modal users, system-operating principles such as coordination are included as priority requests within the decision framework. The system has been developed and tested using both microscopic traffic simulation and in a live network of six intersections in Anthem, Arizona using emerging technology developments in Connected Vehicle systems.

The emergence of wireless communications technology for vehicle-to-vehicle (v2v) and vehicle-to-infrastructure (v2i), called Connected Vehicle Systems in the US, has provided the first opportunity to provide true multi-modal traffic signal control. These technologies allow equipped travelers, vehicles or pedestrians/bicycles, to receive infrastructure information (a MAP) on the basis of which they can determine the arrival approach, service movement (traffic signal phase), and estimated time of arrival that can be used to form a request for priority. At any time, there could be several active requests for priority from different modal travelers at an intersection and in a corridor.

The responsible operating agency must establish a policy for each equipped section of traffic signals that determines the relative importance of different modes of travel. For example, one section might be selected to be pedestrian and transit friendly and another section might be selected to be truck friendly. This priority policy would impact how the signal timing is adapted to accommodate the multiple active requests for priority.

This paper explores the ability of the section priority policy within the unified priority control decision framework for multi-modal travelers to provide improved quality of service for each mode within the structure of the priority policy.

Introduction and background

The need to manage multimodal transportation systems efficiently and sustainably has recently become imperative due to the continuous growth in traffic demand that exceeds network capacities in many cities. Actuated traffic signal control is widely available in urban networks where different conflicting movements of vehicles at intersections are controlled by phases that are called by detectors when vehicles are present. Actuation allows the signals to be responsive to the presence and flow of vehicles, but it doesn't discriminate between different modes of vehicles. In North America, traditional traffic signal control logic has provided priority for different modes through fundamentally independent mechanisms when the special service is requested. Generally these control mechanisms have been based on serving requests on a first-come-first-serve basis rather than based on a policy that sets a preference for one mode over another.

Traditionally, preemption and transit signal priority (TSP) have been the most widely used priority control strategies. Preemption strategies are typically used at highway-rail crossings [1] and for emergency vehicles [2]. Preemption control logic provides a very high level of priority where consideration for other modes and other requests are generally ignored. Coordination is interrupted; pedestrian clearance intervals can be shortened; vehicle phases can be terminated and/or skipped. These treatments are necessary when a heavy rail vehicle is approaching a roadway and a queue of vehicles may be spilling back across the tracks. Traditionally, preemption requests are served in a first-come-first-served manner with a possible override for one approach over another. This leads to inefficient ways of treating conflicting requests, when two or more requests are active at the same time at an intersection from conflicting approaches. Although emergency vehicle operators are trained to be observant and vigilant, there have been cases in which two emergency vehicles have collided in an intersection [4]. Statistics show that almost 13% of the firefighters and police officers who lost their lives in the line of duty are killed in vehicle-related incidents [5]. This reveals the importance of safety issues in traffic signal priority systems.

Transit signal priority (TSP) has been used with some success as a tool to improve transit performance while attempting to limit, or minimize, the impact on vehicular traffic [10,11]. There has been significant research about designing and evaluating TSP systems reported in the literature [6,9]. Some of these systems have been implemented and operated in cities around the United States, Europe, and other parts of the world [10-12]. TSP can be classified into three categories: passive priority, active priority, and adaptive or real-time priorit*y* [9]. Passive priority operates continuously regardless of whether the transit vehicle is present or not [6]. Active priority strategies provide priority service when a transit vehicle sends a priority request [13]. Adaptive or real-time TSP strategies provide priority while trying to optimize a given performance criteria including person delay, transit delay, vehicle delay, and/or a combination of these criteria [14]. Typically, a priority strategy includes extending a phase to allow a transit vehicle to pass or terminate conflicting phases allowing early service to reduce delay [15-17]. A mixed integer nonlinear program was formulated that minimizes the total person delay at the intersection while assigning priority to the transit vehicles based on their passenger occupancy [25].

Consideration of priority control in a more general framework allows for several different modes of travelers to request priority at any time and for other traffic control operating principles, such as coordination, to be considered within an integrated signal timing framework. The NTCIP Signal Control and Prioritization standard [26] establishes a framework for multiple models of travelers to send requests for priority service as they approach an intersection or travel within a signal control section. Operating principles, such as coordination, which are typically not considered priority considerations, can be included in the framework by considering a platoon of vehicles moving along a route as eligible for priority. Similarly, pedestrians can be considered for priority if they are capable of sending a request (e.g. using a nomadic device or infrastructure sensor).

Given a collection of priority requests, the signal control logic must determine the “best” way to time the signals to accommodate the collection of priority requests and traffic control objectives. Establishing this priority signal control policy requires understanding of how the importance and impact of each request affects the performance of the overall system. A signal control policy might be established that gives transit and pedestrians priority over trucks and passenger vehicles in one section and priority for trucks over passenger vehicles and transit in another section. It is assumed that railroad priority will have the highest level of consideration and the emergency vehicles might have the next highest level of consideration.

Within the each mode there may be a hierarchy of importance that is desired within a policy. For example, bus rapid transit might be considered as more important than express transit or local transit. Late buses that are highly occupied might be more important that on-time buses or low occupancy buses. Heavy freight vehicles might be more important than light freight vehicles. Disadvantaged pedestrians might be considered more important than other pedestrians, bicycles, passenger vehicles, trucks, and emergency vehicles.

Although signal priority control strategies are applied worldwide, little effort has been spent on the multiple priority requests scenarios [18-21, 25]. Integration of the multiple requests for priority and the desire to operate signals as part of a coordinated system indicates there is a need for new signal control logic. Motivated by recent advances in vehicle positioning, V2X communications, and DSRC technology, this paper addresses the development of a policy based integrated priority control framework for multi-modal traffic signal control [3].

Multi-Modal Optimization Model

This paper is based on extension of the priority formulation from [20,22]. Assume that there are m different modes of travelers, each one with a corresponding level of importance, denoted I^m, that depend on the established priority policy.

Modes	Level of Importance
Rail	l^R
Emergency Vehicles	l^{EV}
Transit	l^{Trt}
Trucks	l^{Trk}
Passenger Cars	l^{Car}
Pedestrians	l^{Ped}

Table1: Modes level of importance

Based on an active set of priority requests from the different models and the current state (phases and green times served) of the controller, the decision variables are the phase durations, g_p, that allow each priority request to be assigned to be served in a given cycle. The solution is evaluated by the total delay of assigning request j of mode type *m* that requested phase p to cycle k. Binary variables for this assignment are denoted θ_{jpk}^{m}. The objective function is to minimize the total weighted delay of the different modes. The delay for request j of mode type m that is served is denoted ${d^m}_j$ and the coordination delay for coordinated phases phase p in cycle k is denoted ${d^c}_{pk}$. The total delay of all requests of type m is $D_m = \sum_j {d^m}_j$.

Each priority request is characterized by an estimated arrival time and desired service phase. Since the actual vehicle arrival time may be uncertain, each priority request is characterized by an uncertainty interval with unknown distribution, rather than a point of time. The range for each request has a lower and upper bound denoted $[\underline{R}_j, \overline{R}_j]$. This range would be given when a request is communicated from an equipped vehicle to the infrastructure system (v2i).

The signal controller model is based on the standard North American NEMA dual-ring, eight-phase controller. The phase precedence model formulation was developed in [18]. Minimum and maximum green times for each phase p, are considered as $g_{min}(p)$ and $g_{min}(p)$, respectively. The sequence of phases in each ring is assumed fixed and phase skipping is not allowed. This is a reasonable assumption since phase rotation and skipping can cause confusion to the motorist, loss of coordination, and long delay to the traffic stream [6]. Since future vehicle actuations are unknown at the time of optimization, priority control and vehicle actuations are both considered in the optimization. For this purpose, a green extension time variable a_{pk}, for actuated control at phase p during cycle k is considered. Vehicle actuation allows phases to be extended or terminated on the basis of vehicle presence. Since the signal timing required to serve the priority requests could allow multiple phase durations, the ability to accommodate vehicle actuations improves the robustness of the solution.

The mathematical model would be:

$$min_{g,\theta} \quad \alpha(\sum_{m,} w^m D_m) + \beta(\sum_{p,k} d^c{}_{pk}) - \gamma(\sum_{p,k} a_{pk}) \qquad (1)$$

s.t. 1) Precedence constraints
2) Cycle selection constraints
3) Delay evaluation constraints

The objective function consists of three terms: total priority request delay, coordination delay, and actuation flexibility. $w^m, \alpha, \beta, \gamma \geq 0$ are weighting factors that form the priority policy reflecting the importance of each type of mode and delay. (The details of the constraints are not presented in this paper. The reader is referred to [20], [22]).

An intuitive method for visualizing and evaluating the phase timing given a set of priority requests, called the phase–time diagram, was introduced in [16]. Given the previous assumption of a fixed-phase sequence, a phase–time diagram is constructed with one horizontal axis representing time and two vertical axes representing the phases in each of two rings (the left axis is Ring 1 and the right axis is Ring 2), as shown in Figure 1. The origin denotes the current time and current phase, which is shown as the start of Phases 1 and 5, but could be any feasible phase combination. Phases in Ring 1 are evenly distributed on the left vertical axis in a sequence starting from the current phase; the phases in Ring 2 are shown on the right vertical axis. On the basis of the initial settings, the properties of the phase–time diagram are listed below:

- Physical meaning of arc slope: Nodes represent phase transition events, and horizontal arc lengths represent phase duration. Because the phases are evenly distributed, the slope of the arcs determines the phase duration. If a phase times for the minimum time, the arc will be short with a high slope, $1/g_{min}(p)$, where $g_{min}(p)$ is the minimum green time for phase *p* in cycle *k*. If a phase times for the maximal time, the arc will be long with a low valued slope $1/g_{max}(p)$.
- Feasible region: Any piecewise line starting from the origin represents a signal plan in the phase–time diagram. However, the feasible region of the signal plan is bounded in a fan-shaped area by the shortest path (fastest timing as determined by each phase's minimal green times) and the longest path (slowest time as determined by each phase's maximal green times). Any piecewise linear path through each phase between the shortest and longest path is feasible. The black dashed lines in Figure 1, show this feasible region. The green lines are the piecewise green path through phases.
- Request representation: A priority request is associated with a desired service time, and service phase p is denoted as R_{jp}, which represents the desired time of service of the jth request for phase p. Any request R_{jp} will be served in one of the future cycles during phase *p* depending on the realization of the signal plan. R_{jp} can be depicted as cyclic serving bars (CSBs) on the phase–time diagram. Each CSB has a lower and upper bound corresponding to request *j*, $[\underline{R}_{jp}, \overline{R}_{jp}]$.

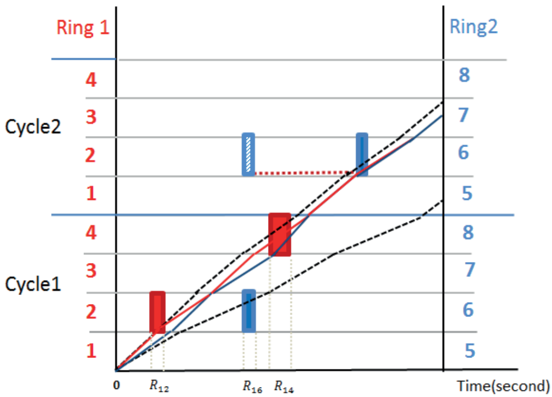

Figure 1: Phase-time diagram representation of dual-ring controller

Three priority requests, R_{12} , R_{16} and R_{14} are shown as CSBs in Figure 1. The lower and upper bound corresponding to each request is described as a pair in time axes. The data is the same as the test problem of Table 2 below. The timing plan (decisions) is shown as red and blue lines. Delay is shown by horizontal dashed line. The first and third requests are served in Cycle 1. The second request is delayed and is served in second Cycle 2.

Methodology

The goal of this section is to propose a method to investigate the delay of different modes within a policy as characterized by $w^m, \alpha, \beta, \gamma \geq 0$. In general, there is no solution that minimizes all of the modal delays simultaneously. Only in an ideal case would a single solution for a multi-objective problem minimize all of the competing objectives.

To understand the competing behavior, consider an optimum signal timing plan that minimizes the delay of a single mode *m*, denoted D^*_m. This consideration may, or is likely to, increase the delay of the other modes. It is desired to obtain a signal timing plan such that it cannot be dominated by any other signal timing plan. The non-dominated solutions (non-dominated signal timings) can be found by varying the weights of each mode or by minimizing the cumulative delay of each mode while constraining the other modal delays to their optimum level. This procedure leads to a Pareto frontier that is constructed of non-dominated solutions [21].

The problem can be reformulated as a multi-objective optimization problem as follow:

$$Min\left(D_1(g,\theta), D_2(g,\theta), \ldots, D_m(g,\theta)\right) \qquad (2)$$

where (g,θ) is a feasible signal timing and request assignment solution and $D_m(g,\theta)$ is the delay associated with the active requests from mode m. Solution (g,θ) is said to dominate solution $(\acute{g},\acute{\theta})$ if and only if:

$$D_i(g,\theta) \leq D_i(\acute{g},\acute{\theta}), \forall i \in \{1,\ldots,m\} \qquad (3)$$

$$D_j(g,\theta) < D_j(\acute{g},\acute{\theta}), \exists j \in \{1,\ldots,m\} \qquad (4)$$

The following algorithm generates Pareto frontier points by investigating all possible assignment of requests to cycles. The Pareto diagram (see Figure 2 bellow) presents non-dominated solutions of average delay per passenger car with respect to the total active request delay. First, the total active request delay of each assignment of requests to cycles is minimized. Then, by constraining the delay of each request to its minimum value for each possible assignment, the average delay per passenger car is minimized. In the current study, only two cycles are considered so there is at most 2^n different solutions for *m* modes, where *n* is the total number of requests. Also, since it is assumed that there are only a few active requests, the number of possible assignments is manageable. Some of the assignments may be infeasible and can be ignored.

The desired role of mode weights in formulation (1) is to implement a policy that favors one mode over another. There are critical modes weights that force requests to be assigned to different cycles, but as long as the assignments are fixed, changing the weights does not affect the Pareto points.

Consider two problems: PI and PII.

PI:

$$Z_{PI} = Min_{g,\theta} \sum_m D_m \qquad (6)$$

which is the minimization of un-weighted delays of all active requests from different modes excluding passenger cars.

PII:

$$Z_{PII} = Min_{g,\theta} \left(\frac{D^{Cars}}{TotalCars}\right) \qquad (7)$$

which is the minimization of average delay per vehicle for passenger cars.

Algorithm:

1) Solve PI for all different combinations of request-cycle assignments to cycles, θ_{jpk}^{m}. Assume D_m^{*n} is the optimal delay for mode m in the feasible assignment $i = 1, \ldots, 2^n$. Also, assume that $Z_{PI}^{*i} = \sum_m D_m^{*i}$ is the total minimum delay for each assignment.

2) For each feasible request-cycle assignment $i = 1, \ldots, 2^n$, solve PII subject to the additional constraint:

   $$D_m = D_m^{*i} \quad ; \forall m \qquad (8)$$

   Assume Z_{PII}^{*i} is the minimum value of problem PII for the ith assignment. Store all the possible points as pairs, (Z_{PII}^{*i} , Z_{PI}^{*i}), $i \in \{1, \ldots, 2^n\}$.
3) Solve PII with no priority delay constraint (8) and assume its minimum value is Z_{PII}^{*}. In this problem, the average vehicle delay for passenger cars is minimized without considering other modes. Calculate the delay of the other modes based on the signal timing plan obtained from solving problem PII. Assume the summation of these delays is Z_{PI}^{PII}. Add the new point $(Z_{PII}^{*}, Z_{PI}^{PII})$ to the previous stored points.
4) Among at most $2^n + 1$ obtained points, select the maximum number of points that satisfy conditions (3) and (4) as non-dominated solutions of the Pareto frontier.

Numerical Results

It is assumed that there are only two modes requesting priority: Transit vehicles or Trucks, and they request the only through movement phases 2, 4, 6 or 8. It is assumed that each passenger car can generate a request and its range of arrival time is determined based on the traffic conditions The minimum green time for left turns (phases 1, 3, 5, and 7) is 7 seconds and 15 seconds for through movement phases (2, 4, 6, and 8). The maximum green time for each through movements is 25 seconds and is 15 seconds for each left turn. The total red and yellow time is 5 seconds. Also, it is assumed that the range of each CSB for each requests is less than the maximum green time for the requested phase, $\overline{R}_{jp} - \underline{R}_{jp} \leq g_{max}(p)$, for all phases p and all requests j. Problems are solved using GAMS on a computer with 2.14 GHz processor. It should be noted that allowing every passenger vehicle to generate a priority request results in a very complex optimization problem that cannot be solved in real time. This formulation is used only in this study of the policy structure. Passenger vehicles would normally be accommodated through coordination requests and vehicle actuation, as considered in the initial formulation.

Three active requests are considered in a set of test problems. Their earliest arrival times are generated randomly. The time range is either 5 or 10 seconds. Table 2 lists the active requests table for one particular test problem among. Figure 1 depicts the time-phase diagram of this example.

Request	Request	Range	Requested Phase
1	Transit#1	[10,15]	2
2	Transit#2	[42, 47]	6
3	Truck	[50, 60]	4

Table 2: Three active requests, their arrival range and requested phase

In this paper, coordination delay was not considered, so $\beta = 0$. Also, since passenger cars requests are generated deterministically, green extension delay is also ignored, so $\gamma = 0$. According to the proposed algorithm, an un-weighted delay function is considered, $\alpha = 1$ and $w^m = 1$ for all modes m. In fact, different mode weights do not affect the number of Pareto frontier points.

Based on the algorithm defined above, there are $2^3 = 8$ possible assignments and therefore 9 points to be investigated.

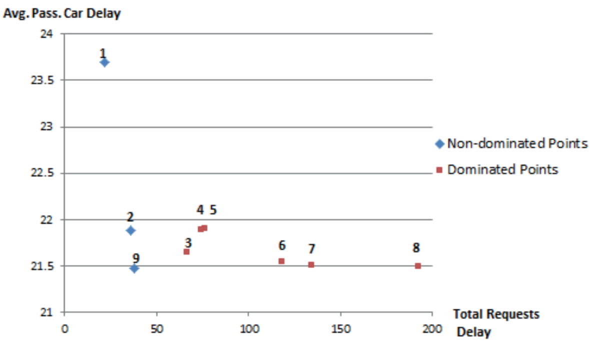

Figure 2: Non-dominated points and dominated point of request Table 1

Figure 2 shows the total requests delay with respect to the average passenger car delay for these nine points. The total request delay of points 1 through 8 are obtained from step 1 of the algorithm. Their corresponding average passenger car delay is obtained from step 2. Step 3 finds point 9 that has minimum average passenger car delay. As it is distinguished from other points in Figure 2, point 3 is dominated by point 9 since point 3 has higher total requests delay and higher passenger cars delay. Based on equations (3) and (4), points 1, 2 and 9 are not dominated by each other and construct the Pareto frontier. As an example of the non-dominating criteria, comparing point 1 and 2 shows that point 1 has smaller total priority delay but higher average passenger car delay. So, these two points require a decision maker to state a preference. If decision maker desires that

$$\frac{Avg\ Passenger\ Car\ Delay}{Total\ Requests\ Delay} > \frac{21.87}{36} = 0.61,$$

(left side of blue dashed line is desired), then point 1 is the best solution. If decision maker desires to have at most 21.75 seconds for average passenger car delay and also

$$\frac{Avg\ Passenger\ Car\ Delay}{Total\ Requests\ Delay} < 0.61,$$

(left side of blue dashed line and top of red dashed line is desired), then point 2 is the best solution.

Point	Transit Vehicles Delay	Truck Delay	Avg. Cars Delay	Assigned Cycle	Weights Ratio
1	$D_{Trs}^{*1} = 10$	$D_{Trk}^{*1} = 12$	$Z_{PII}^{*1} = 22.16$	C1,C1,C1	$\frac{w^{Trk}}{w^{Trs}} < 2.125$
2	$D_{Trs}^{*2} = 36$	$D_{Trk}^{*1} = 0$	$Z_{PII}^{*2} = 21.87$	C1,C2,C1	$\frac{w^{Trk}}{w^{Trs}} > 2.125$
9	38	0	$Z_{PII}^{*} = 21.46$	C1,C2,C1	$\frac{w^{Trk}}{w^{Trs}} > 2.125$

Table 3: Modes delay and cycle assignments of request Table 1

Table 3 shows the modes delay and cycle assignments for Pareto frontier points. Point 1 results in all requests being assigned to cycle 1. Considering formulation (1),

if $\frac{w^{Trk}}{w^{Trs}} < 2.125$, then all mode requests would be served in first cycle (point 1 is obtained).

If this ratio is in a level above the critical value 2.125, the assignment changes and it leads to other Pareto points (point 2 or 4).

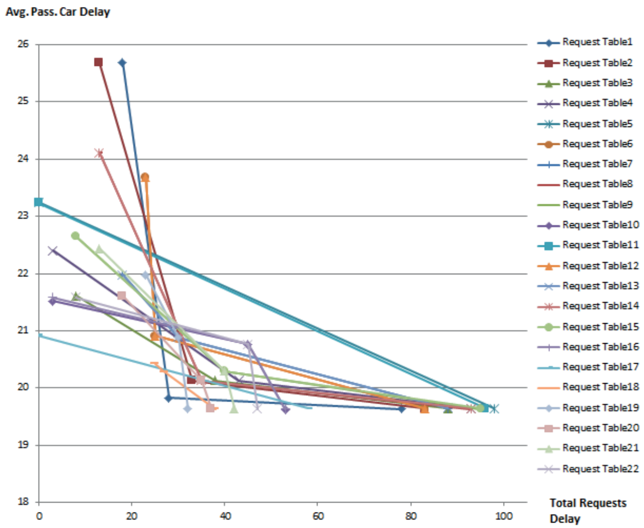

Figure 3: Pareto frontier of 22 request tables

Figure 3 illustrates Pareto frontiers of 22 different request tables each one with three requests. Requests are from Truck and Transit vehicles. Pareto points are connected for each table to illustrate the relationship between Pareto points. It is not possible for passenger cars to have average delay less than 19.64. Depending on the request-cycle assignment, each request table may have 2 or 3 non-dominated points. The Pareto frontier of request table 11, has just two points and the active requests can be severed without any delay.

This figure helps decision makers understand the complex behavior of priority control and the options available to find a non-dominated point to not only keep total priority delays less than a predetermined value, but also keep average cars delay in a minimum acceptable value

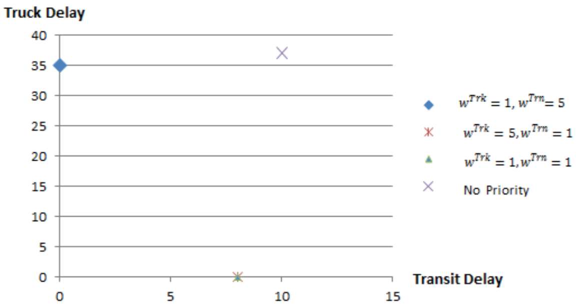

Figure 4: Transit-Truck delay diagram

Figure 4 shows Truck delay with respect to Transit delay of the first request table illustrated in Figure 3. The number of Transit requests is 2 and the number of Truck request is 1. Different weighting policies may result in different points that reflect the decision makers policy. Un-weighted delay function or any weighting policy in favor of Transit vehicles leads to zero delay for Transit vehicles. On the other hand, if Trucks are 5 times more important than Transit vehicles, then they get zero delay. In the case that no priority is considered, both of Trucks and Transit vehicles are delayed (crossed line point). In this case, passenger cars have the minimum delay.

Conclusions

This paper examines the development of a multi-modal signal control policy for the priority signal-timing problem. An algorithm is designed to obtain Pareto frontier of average passenger cars delay respect to total priorities delay. Test problems for priority requests of two modes Transit and Truck vehicles are generated. The Pareto frontier of several test problems is obtained. For a specific test problem, dominated and non-dominated solutions are illustrated. It is shown that there are critical modes weights that force requests to be assigned to different cycles and as a result, different Pareto frontier point can be reachable. The obtained modes weights and Pareto frontier points help decision makers to set a policy that favors one mode over another.

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Part III: Technologies, Applications and Solutions

Comparative Evaluation of Traffic Signal Optimizations and Green Light Optimized Speed Advisory Systems

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Abstract

The highest fuel consumption on urban arterials is associated with driving in congested traffic, characterized by higher speed fluctuations and frequent stops at intersections. One of the ways to reduce excessive stop-and-go driving on urban streets is to optimize signal timings. More recently new methods in traffic signal optimization have incorporated changes in drivers' behaviour to achieve optimum performance at signalized intersections. One such application is called GLOSA - Green Light Optimized Speed Advisory. GLOSA is a method that uses traffic signal information to provide drivers (through infrastructure-to-vehicle communication) with speed advice for a more uniform commute with less stopping time through traffic signals. Recent results showed that a GLOSA system works efficiently only if exact durations of signal phases are known. Objective of this paper is to further evaluate performance of a GLOSA system in real-world-like conditions. Could GLOSA and similar speed-advisory methods replace a need for retiming traffic signals? This paper attempts to answer this question by applying a GLOSA approach on a set of (optimal and suboptimal) signal timings from an urban corridor in Salt Lake City, UT. A VISSIM model of a 5-intersection corridor, calibrated and validated with field data, is used to test two types of signal timings: fixed and actuated. The field signal timings from the case-study corridor are optimized by VISGAOST, a Genetic Algorithm Stochastic Optimization tool based on VISSIM evaluations. The results suggest that the GLOSA does not have an equal effect on traffic with fixed-time and actuated-coordinated signal timings, where the latter ones are collected as averages from historic records and embedded into the GLOSA algorithm. If the phase durations are predictable, as with fixed-time signal timings, then GLOSA has a significantly positive effect on number of stops and fuel consumption. However, if accurate signal timings are not known then it is likely that GLOSA will not bring a positive impact on traffic performance.

Keywords: connected vehicle technology, traffic signals, advisory speeds, fuel consumption, traffic delay.

Introduction

The highest fuel consumption on urban arterials is associated with driving in congested traffic, characterized by higher speed fluctuations and frequent stops at intersections. One of the ways to reduce excessive stop-and-go driving on urban streets is to optimize signal timings [1]. More recently new methods in traffic signal optimization have incorporated changes in drivers' behaviour to achieve optimum performance at signalized intersections. Connected Vehicles (CV) technology provides a two-way wireless communication environment enabling vehicle-to-vehicle and vehicle-to-infrastructure communications, which can be used for a variety of mobility and safety applications. One such application is called GLOSA - Green Light Optimized Speed Advisory [2]. This is a system that uses timely and accurate information about traffic signal timings and traffic signal locations to guide drivers (through infrastructure-to-vehicle communication) with speed advice for a more uniform commute with less stopping time through traffic signals. Recent results [2] showed that a GLOSA system works efficiently only if exact beginning and ending times of green phases are known (e.g. possible only with fixed-time signals). If a system is not supplied with exact timing information (e.g. as in the case of actuated signals), or approximate green times are approximated from historic records, GLOSA systems may not work optimally.

Objective of this paper is to further evaluate performance of a GLOSA system in real-world-like conditions. In real-world operations traffic signals are rarely working optimally. As soon as traffic signals are retimed traffic conditions may change and signals may not perform optimally. In situation when retiming of traffic signals is becoming more financially difficult than ever before, and when new emerging technologies (such as GLOSA) may be available sooner than we expect, one may question if the existing practice of retiming signals is still necessary. Could GLOSA and similar speed-advisory methods replace a need for retiming traffic signals? Instead of adjusting signals to work with existing (ever-changing) traffic flows, could we 'adjust' speeds of incoming traffic flows to work with the existing signal timings? Which approach would bring higher operational benefits (reduced delays, stops, and fuel consumption)? What would be operational benefits of combining these two approaches (retiming signals and applying GLOSA)? This paper attempts to answer all of these questions by applying a GLOSA approach on a set of (optimal and suboptimal) signal timings from an urban corridor in Salt Lake City, UT.

Review of previous research

Numerous studies have demonstrated the potential of V2V communication for improving fuel efficiency of vehicular traffic on signalized streets; authors focus here on a few of those that are most relevant for this paper. Widodo et al. investigated impact of environment-adaptive driving with and without inter-vehicle communications [V2V] [3]. A simplistic model for driving behavior and fixed-time traffic signals are applied in this study. Simulation results showed that environment-adaptive driving is effective to reduce both of the average fuel consumption and vehicle emissions. In a similar study Sanchez et al. investigated impact of a GLOSA-like algorithm on fuel consumption in an I2V environment [4]. Simulation results show that a 30% fuel consumption reduction can be obtained if just one out of ten cars uses the proposed driver model [4]. Wegener et al. added two levels of complexity to GLOSA-like approaches [5]. They simulated traffic dynamics in a traffic simulator [Sumo] while communications in vehicular ad-hoc networks [VANETs] were modelled in a network communication simulator [TraCI] [5]. Li et al. [6] investigated an impact of an advanced driving alert system that provides traffic signal status information to help drivers avoid hard braking at intersections. Authors conducted experiments on two-intersection simulation model and concluded that the system can save around 8% in fuel consumption in medium traffic congestion. In a series of studies Mandava et al. [7], Barth et al. [8], and Xia et al. [9] developed and tested an arterial velocity planning algorithm [later called “Dynamic ECO-Driving”] that provides dynamic speed advices to the drivers to maximize probability of catching a green when approaching an intersection. The goal was to minimize the acceleration/deceleration rates while ensuring that the vehicle never exceeds the speed limit, while it passes through an intersection without having to stop. The results showed approximately 12% of fuel consumption savings when such “Dynamic ECO-Driving” concept is applied. Tielert et al. coupled the Passenger car and Heavy duty Emission Model [PHEM] with VISSIM, a PTV traffic simulation model, to investigate impact of a GLOSA-like approach on fuel consumption and emissions [10]. The sensitivity analysis identified gear choice and the distance from the traffic light at which vehicles are informed as key influencing factors [10]. The results indicated that a suboptimal gear choice can void the benefits of the speed adaptation [10]. Asadi and Vahidi proposed a predictive vehicle cruise control based on optimization of vehicular trajectories through several downstream traffic signals [11]. The potential impact this signal-to-vehicle communication might have on fuel consumption, emission levels and trip time was demonstrated with three example simulation case studies [11]. Katsaros et al. tested a GLOSA-like scenario in a two-intersection model developed in SUMO [12]. The authors used Fraunhofer VSimRTI [12] to enable an online interface between traffic and communication simulation models. The results showed that as the density decreases, the benefits for fuel efficiency are reduced, but the traffic efficiency on the other hand is increased [12]. Xia et al. [13] tested the “Dynamic ECO-Driving”, both in field experiments and in simulation, at a fixed-time signalized intersection, where a test vehicle communicated with controller through a wireless communication [signal phasing and timing was communicated to the driver to adjust vehicle’s speed when approaching the intersection]. Results from both experiments showed similar benefits in fuel economy, which was around 13.5-14%. In summary, numerous studies have proven effectiveness of GLOSA and similar fuel-saving algorithms based on I2V and/or V2V communication and information from traffic signals. However, most of these studies dealt with fixed-time signal timings [as opposed to field-like actuated signal timings whose green durations may vary significantly] and none of them evaluated how GLOSA works for optimized versus non-optimized signal timings. This study bridges the gap in existing knowledge by addressing these points.

Methodology

Methodologically, this paper applies a novel and simplistic method to derive vehicles’ positions and order in the vehicular queue based on basic kinematic formulas for speed and discharge headways/saturation flow rates. Another significant contribution is the integration of the GLOSA algorithm into a VISSIM C2X platform which provides extra validity to the results considering that VISSIM is one of the most advanced traffic microsimulation tools. The tests are performed on a five-intersection road network whose simulation performance metrics are calibrated and validated to resemble those observed in the field [14].

Simulation Approach

Simulating the GLOSA usually represents a challenge in terms of combining and synchronizing different simulation platforms, e.g. vehicular traffic, network communication and application handling. Details of how GLOSA was modelled in this study can be found elsewhere [2]. Here, we present major assumptions which distinguish this study from other similar studies:

- Simulation framework: Emphasis was given on integration of the two simulations where communication between vehicles and infrastructure was assumed to be ideal and punctual. VISSIM was used to simulate traffic, its Car2X Module represented an I2V communication platform, and the COM Interface was used to retrieve current states of the relevant signal phases. The GLOSA algorithm was written in C++.
- Traffic model: VISSIM [15] is a microscopic, time-step and behaviour-based model developed to simulate urban traffic and public transport operations. The accuracy of a traffic simulation model is mainly dependent on the quality of vehicular modelling, such as the methodology of moving vehicles through the network. In contrast to less complex models that use deterministic car-following logics, VISSIM uses the psychophysical driver behaviour model developed by Wiedemann [15].
- Emission model: Since VISSIM does not generate reliable fuel consumption and emission estimates, Comprehensive Modal Emission Model (CMEM) [16] calculated fuel consumption and emissions of the tested scenarios. A Light Duty Vehicles (LDVs) sub-model was used to estimate vehicle tailpipe emissions (CO, HC, NOx, and CO2) in different modes of vehicle operation (idling, cruising, acceleration, etc.). A fleet consisting of 100% of warm-start LDVs was used for the sake of simplicity.
- Traffic signals: VISSIM has several ways of modelling traffic signal control. Ring-Barrier Controllers (RBC), which reliably emulate [14] standards of the National Electrical Manufacturers Association (NEMA) field controllers, were used.
- Driver behaviour: Two major simulation scenarios were established, each with additional sub-scenarios. In the first scenario, drivers do not receive any speed advisory information and the basic concept of the psycho-physical driver behaviour model developed by Wiedemann [15] is applied. This concept assumes that a driver of a faster moving vehicle starts to decelerate when reaching his or her individual perception threshold when approaching a slower moving vehicle. In the second scenario GLOSA sends speed advisory messages (i.e. desired speed) to each individual driver. It is assumed that all drivers who get a speed advisory message will adjust their speeds accordingly. However, drivers do not react immediately and they

do not reach the exact advisory speed. Once instructed to change the speed all drivers comply (depending on penetration rate) but there are stochastic variations of response time and exact speed which is adopted.

- Performance measures: Three measures are used to evaluate impact of the GLOSA method on traffic performance. Total (network) delay and number of stops from VISSIM; and fuel consumption from CMEM. Also, a Performance Index (linear combination of delay and stops) was used to develop optimal signal timings, as this is a common objective function for signal timing optimization.
- Penetration rate and speed updates: A percentage of GLOSA-equipped vehicle is controlled to monitor the impact of penetration rate on the success of the GLOSA method. Also, frequency of GLOSA's activation (or update of speed advisories) is varied to model how potential computational and/or communicational delays may impact the overall traffic performance.

GLOSA Algorithm

An algorithm developed to implement GLOSA in a VISSIM simulation environment is shown in Figure 1. The application collects information from all vehicles that can communicate with the infrastructure (Car2X vehicles in VISSIM). For each vehicle approaching a traffic signal, the algorithm determines a range of feasible speeds {vMin, vMax} which, if implemented, would enable the vehicle to pass through the intersection without stopping. If the vehicle's current speed is already within this range, the algorithm then examines the next vehicle. In this manner the algorithm avoids sending a speed advisory message unless it is evident that such action would be beneficial (e.g. to clear the intersection during the first green light). Furthermore, in this way GLOSA's computation and communication requirements are reduced which better represent field-like conditions. Thus, the GLOSA algorithm affects only those vehicles (both on major and side streets) that, if continuing to travel with their current speed, would arrive at an intersection during the red signal phase. Those vehicles would be advised to change their speed (within a permitted range {speedMin, speedMax}), in such a way that they pass (without stopping) through an intersection during the green light. To determine if a vehicle will have to stop at the intersection, the current length of the queue at the relevant intersection approach is considered. Vehicular queue on each intersection approach is estimated by considering position of an arriving vehicle and its speed. Since vehicle's position is communicated to 'controller' each second it is easy to know whether a vehicle is on a particular link in front of the signal's stop line. If its speed is lower than 3.6 km/h (5 mph) the program considers that a vehicle is stopped and part of the queue. The queue length is then estimated by simply adding all of the vehicles on a given approach whose speeds are lower than the given threshold. Accuracy of the queue estimation has been validated; it is highly correlated (R^2=0.96; y=1.01x; N=100) to a queue lengths observed visually from simulation model. Discharge of the queue is handled by GLOSA's algorithm variable dischargeHeadway (see Figure 1) based on the approach applied by Greenshield [17] (after first five vehicles the headways level out at 2.1 seconds). If the current signal state is red, the GLOSA will send speed advisories to enable vehicles to pass through the intersection during the next green phase. However, if the current signal phase state is green, an advisory speed may be sent out either for the current phase (if feasible) or for the next green phase.

```
Step 0: Initializing
        N, Number of vehicles in the network (during current time step)
        veh = 0, current vehicle
        stopped(sh) = 0, number of stopped vehicles for each signal head
        newlyStoppedVehicles(sh) = 0, number of vehicles that have stopped in current time step
Step 1: Testing Termination Criteria
        veh = veh+1
        sh = MostRelevantSignalHead(veh)
        IF Found(sh)
                CalculateDischargeHeadway
                IF v(veh) < vMaxStopped
                        stopped(sh) = stopped(sh) + 1
                        IF id(previouslyLastVeh) < id(veh)
                                newlyStoppedVehicles(sh) = newlyStoppedVehicles(sh) + 1
                dist = Distance(veh,sh)
                GO TO Step2
        ELSE
                IF veh < N        GO TO Step 1
                ELSE
                        Exit GLOSA and run next time step of VISSIM Simulation
Step 2: Branching for Speed Advised Calculation
        IF State(sh) = red
                vMin = dist/(remainingRed+aveGreen)
                vMax = dist/(remainingRed+dischargeHeadway)
                RedefineTheSpeedAdvised
        ELSE IF State(sh) = green
                vMin = dist/remainingGreen
                IF (dischargeHeadway <= remainingGreen) & (dischargeHeadway != 0)
                        vMax = dist/dischargeHeadway
                ELSE
                        vMax = speedMax
                IF vMin < speedMax
                        RedefineTheSpeedAdvised
        IF ( (speedAdvised not defined)  AND (remainingGreen<dist/desiredSpeed(veh)) )
                GO TO Step 4
        ELSE
                GO TO Step 1
Step 3: Assigning Speed Advisory Message to Current Vehicle
        desiredSpeed(veh) = speedAdvised
        GO TO Step 1
Step 4:Green Phase - Vehicle Arriving during Next Green Phase
        remainingRed = remainingGreen+aveAmber+aveRed
        vMin = dist/(remainingRed+aveGreen)
        vMax = dist/remainingRed
        RedefineTheSpeedAdvised
        GO TO Step 3

Calculation of the discharge headway (CalculateDischargeHeadway)

IF State(sh)=red
```

$$\text{dischargeHeadway} = \sum_{i=1}^{stoppedVehicles} IndividuaHeadway_i$$

```
ELSE IF (noNewVehInQueue)
        dischargeHeadway = previousTimeStepDischarge - timeStep
ELSE
        dischargeHeadway = previousTimeStepDischarge - timeStep +
```

$$\sum_{k=1}^{newlyStoppedVehicles} IndividuaHeadway_k$$

```
Redefinition of the advised speed (RedefineTheSpeedAdvised)

IF (desiredSpeed(veh) < vMin) OR (vMax < desiredSpeed(veh))
        IF (speedMin <= vMax <= speedMax)
                speedAdvised = vMax
        ELSE IF ( vMin <= speedMax <= vMax)
                speedAdvised = speedMax
```

Figure 1: GLOSA Algorithm – Pseudo Code.

One should note here that presented GLOSA algorithm relies on VISSIM providing vehicle's desired speed at each simulation step. For field implementation of similar GLOSA method one would need to derive such speed from vehicles speed history (e.g. a moving average for the last X seconds without any acceleration/ deceleration). If the GLOSA algorithm advises a speed higher than vehicular current speed then the new desired speed will be a minimum of the following two speeds: 1) the speed sufficient for a vehicle to arrive at the beginning of the green phase (vMax), or 2) the maximum allowable speed (speedMax) which is usually 5 miles/hour over the speed limit. An absolute minimum advisory speed can be set in GLOSA in advance. Impact of the minimum practical advisory speed on GLOSA efficiency was tested and discussed in following paragraphs.

Simulation Set-Up and Scenarios

For the evaluation of the GLOSA application a section of the corridor along 3500 South Street in SLC, Utah, was used (Figure 2). A VISSIM model of the study case segment was built, calibrated, and validated based on following field data: signal timings, speed limits, p.m.-peak 15-min turning-movement counts, and queue lengths at some intersections. Speed limits, 15-min turning-movement counts, and queue lengths were used to calibrate the VISSIM model. To validate the model, travel times (floating car with Global Positioning System device) along the arterial were measured while passing times at each intersection were recorded. High coefficients of determination (R^2) for the two pairs of data sets (0.988 for calibration and 0.986 for validation) show that a reliable model of the current traffic conditions on this arterial segment was achieved [14].

Since the five signalized intersections have actuated-coordinated traffic control in the field, unpredictable changes in phase durations hinder the benefits of a GLOSA implementation. To determine the relationship between GLOSA benefits and traffic control types, a series of simulations were conducted for both actuated-coordinated and fixed time coordinated traffic control. Two major scenarios were tested for each of the two basic cases (with GLOSA and without GLOSA). The first scenario assumes that the signal timing plans are fixed (Fixed Timings) where lengths of green, red, and yellow intervals remain constant. The second scenario considers actuated-coordinated signal timings (from the field) where green and red intervals may change based on individual actuations of the arriving vehicles (Actuated Timings). It should be noted that most of the recent studies on GLOSA mostly assume fixed-time signal timings which are known in advance and completely predictable [3-13].

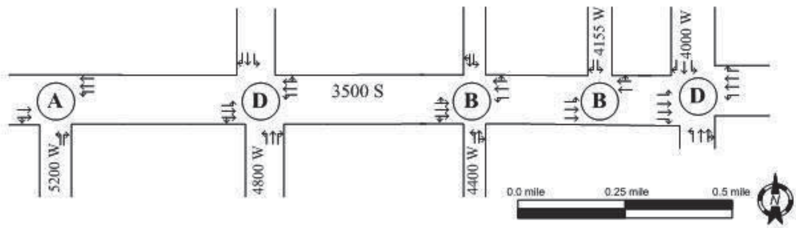


Figure 2: Study Corridor along 3500 South Street in SLC, Utah.

Preliminary Tests with GLOSA

Considering that fixed-time signal timings are constant their use in a GLOSA application was straightforward. These signal timings were developed in such a way that their green splits are equivalent to the green splits of the actuated-coordinated signal timings from the field (as recommended by relevant engineering practice). However, use of actuated-coordinated signal timings was much more complex. Unlike fixed-time signal timings, actuated-coordinated signal timings vary from cycle to cycle where actual durations of individual phase's green depends on minimum and maximum green times, vehicle extension, and actual vehicular actuations. Since, some of these variables cannot be known in advance (e.g. vehicular actuations) it is difficult to predict actual duration of a phase's green. Hence, authors tested several statistics from the historic signal timing records (simulation was run and those statistics were collected) which included 15^{th}, 50^{th}, 75^{th} and 95^{th} percentiles and mean values of executed green times for each signal phase for each signalized intersection. These statistics were based on VISSIM's records of signal timing changes – an output file which generates frequency histograms of red and green intervals for individual signal phases. In the field, similar statistics (e.g. mean green times) are sometimes reported as historic records by central traffic control systems (e.g. Split history in ATMS.Now).

Before proceeding with further GLOSA experiments it was necessary to test impact of various operational strategies on GLOSA's performance. More specifically, these operational strategies refer to: GLOSA's activation frequency, penetration rate of I2V-equiped vehicles, minimum practical advisory speed, and statistic which is used to estimate green durations for actuated-coordinated controllers. The GLOSA activation frequency refers to how frequently (every 1, 2, 5 or 10 seconds) a GLOSA algorithm is executed and speed advisory messages are communicated to vehicles. A practical reason for these tests was to model GLOSA implementation in a field-like environment where potential computational or communicational delays may prohibit GLOSA from implementing frequent and accurate speed advisories. Penetration rate simply represents a percentage of vehicles which are equipped to participate in GLOSA implementation. Obviously, if not 100 % of population is I2V enabled GLOSA will derive advisory speed with incomplete information about position and speeds of the arriving vehicles, which reduces its accuracy and efficiency. A range of minimal advisory speeds (10-25 mph) was tested simply because authors wanted to see how this variable impacts GLOSA performance. If GLOSA does not require that speed is significantly reduced when a vehicle cannot reach signal during current green this would be a preferable option. Finally, it was important to find out which of the statistics from historic actuated green times can be used as the best predictor of how much green time will last when such information cannot be known for certain (as with actuated signals). Figure 3 shows results from these experiments. The findings confirmed common-sense expectations:

- Lower activation frequencies enabled higher sampling rates and improved GLOSA's performance (stops and delays are lower).
- Increased penetration rate increased accuracy of GLOSA traffic/queue estimations and also improved GLOSA's performance.

- Lower minimum advisory speed also improved GLOSA's performance because lower speeds impose fewer restrictions on GLOSA when proposing an optimal speed for arriving vehicles.
- Finally, when historic mean green times are used to estimate future actuated green times results are better than if of the percentiles (including median) are used.

Optimizations of Signal Timings

Both fixed and actuated-coordinated (field) signal timings were optimized (retimed) by using VISGAOST, a Genetic Algorithm Stochastic Optimization tool based on VISSIM evaluations [18] (20 signal timing plans, 120 generations). Purpose of the optimization/retiming was twofold: 1. to evaluate performance of the best-case signal timings when compared to GLOSA, and 2. to enable further GLOSA implementation on optimized/retimed signals in order to observe combinational effects of the two approaches (GLOSA and retiming). VISGAOST was used to ensure that there are no inconsistencies which occur when a tool with different traffic model (e.g. Synchro or TRANSYT-7F) is used to optimize signals which run in VISSIM. Figure 4 shows results of stochastic VISGAOST optimization processes. Actuated signal timings (both initial and optimized) outperformed fixed timings by about 18%.

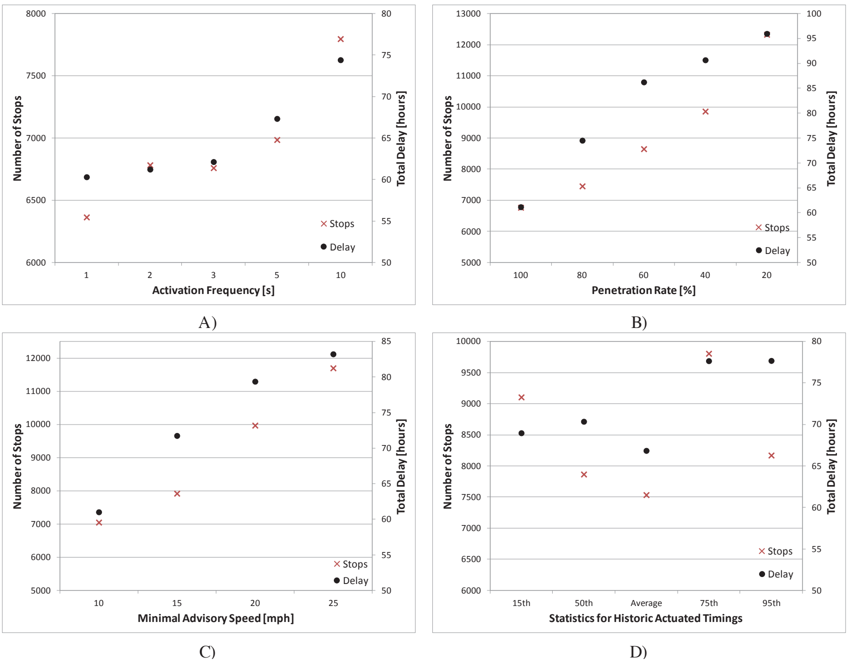


Figure 3: GLOSA Performance for range of: A) Activation Frequencies, B) Penetration Rates, C) Minimal Advisory Speeds, D) Statistics for Estimation of Green Intervals.

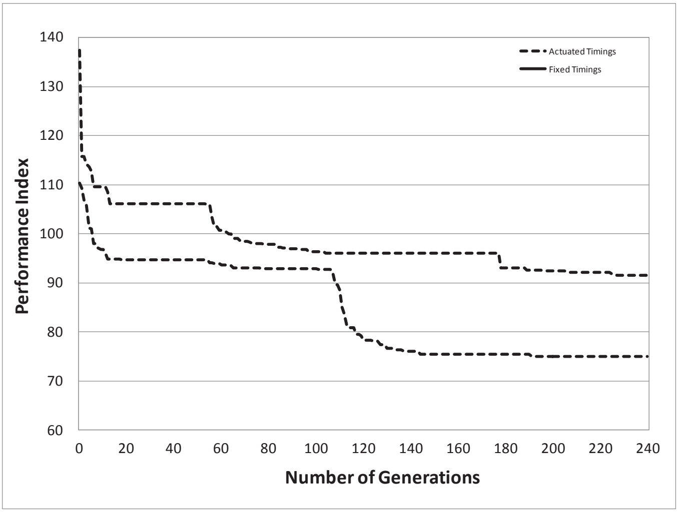


Figure 4: Evaluations of signal timings during stochastic VISSIM-based optimizations.

Eight signal-timing and speed-advisory scenarios were evaluated in further experiments (four for each of the fixed-timings and actuated-timings options):

- Initial timings – these were scenarios with signal timings either taken from the field (actuated) or developed equivalently (fixed); no speed advisory (GLOSA) applied.
- GLOSA – speed advisory algorithms implemented on initial timings with following variables: Activation frequency – 1 second, Penetration rate – 100 %, Minimal advisory speed – 10 mph, Statistics used for estimation of green intervals for actuated signals – mean green intervals.
- Optimized – signal timings which resulted from VISGAOST optimizations (Figure 4); no speed advisory (GLOSA) applied.
- GLOSA & Optimized – speed advisory algorithms implemented on optimized timings with the same variables (Activation frequency, Penetration rate, etc.) as above

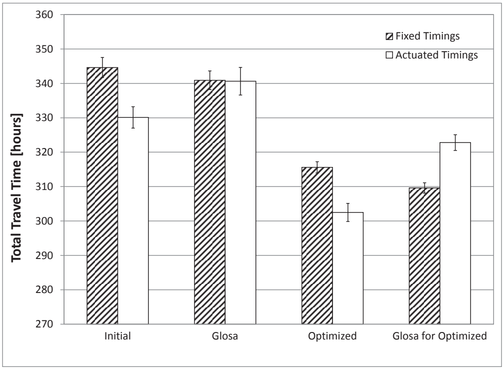
Evaluation results and discussion

All of the scenarios were evaluated through 10 randomly seeded runs in VISSIM 5.3. Each simulation run was 1 hour (PM peak hour) and 15 minutes (warm up time) long. Finally, each of the scenarios was separately tested for fuel consumption and emission estimates, which required post-processing of vehicular trajectories from VISSIM in CMEM (more information can be found elsewhere [18]).

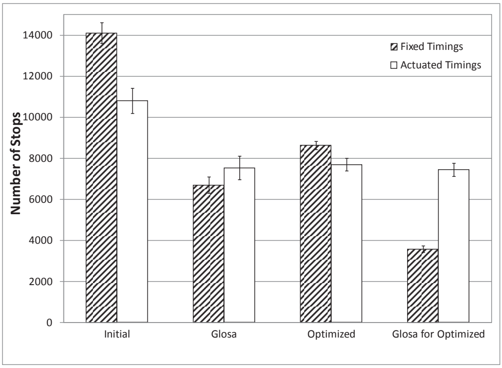
Figure 5 shows simulation results: mean values accompanied with standard deviations (error bars) for total network travel time, number of stops, and fuel consumption. Part A of Figure 5 show that travel times are improved more when signals are optimized than if GLOSA is applied. This result is logical as the GLOSA algorithm slows down vehicles (that would arrive on red) to avoid stops at this signals. This approach has only a small positive net impact on total travel time. Results for stops (part B of Figure 5), on the other hand, show that GLOSA is more effective than optimization of signal timings. This is again a logical finding considering that signal optimization does not attempt to reduce stops at each intersection but seeks a system/network optimum in terms of delay and stops. When fuel consumption is considered results (part C of Figure 5) are somewhere in the middle – which is logical as fuel consumption is correlated both to stops (acceleration/deceleration driving cycles) and travel time (more time in travel, more fuel consumed).

However, logical reasoning from above can be applied only to fixed-time signal timings. Findings for actuated signal timings are much more difficult to interpret due to stochastic nature of the duration of green phases. One can observe from Figure 5 that actuated timings start from a better initial position than fixed timings. Further, whenever these actuated timings work without GLOSA, they outperform fixed timings (e.g. see actuated vs. fixed timing for "Initial" and "Optimized" scenarios). However, whenever GLOSA is applied, for like scenario, fixed timings outperform actuated timings. These results are consequence of the fact that actuated green times cannot be accurately estimated from their historic statistics; no matter that the statistics were developed for the same traffic conditions.

Finally, when GLOSA is implemented on signal timings which are already optimized/ retimed, this is beneficial for fixed timings and not beneficial for actuated timings. Figure 5 shows that travel time and fuel consumption are even worse when GLOSA is applied on optimized actuated timings. Table 1 shows exact benefits (as percentage in travel time, stops and consumed fuel) of each of three 'action' scenarios when compared to initial ('no action') conditions. In general, magnitude of fuel consumption savings is similar (around 12%) to findings reported elsewhere [6-9] but only in the best case scenario – when GLOSA is applied to optimal fixed-time signal timings.



A)



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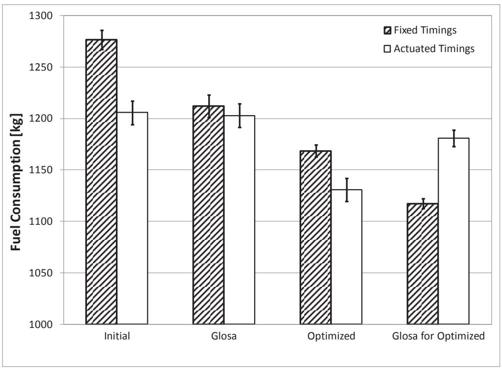

C)

Figure 5: Evaluation Results – A) Travel time, B) Number of Stops, C) Fuel Consumption.

	Retiming			GLOSA			Retiming & GLOSA		
	Travel Time	Stops	Fuel	Travel Time	Stops	Fuel	Travel Time	Stops	Fuel
When compared to initial signal timings									
Fixed Timings	8.4%	38.9%	8.5%	1.1%	52.5%	5.0%	10.2%	74.6%	12.5%
Actuated Timings	8.4%	28.8%	6.2%	-3.2%	30.3%	0.2%	2.2%	31.1%	2.1%
When compared to retimed signal timings									
Fixed Timings				-8.0%	22.3%	-3.7%	1.9%	58.5%	4.4%
Actuated Timings				-12.6%	2.0%	-6.4%	-6.7%	3.1%	-4.4%
When compared to GLOSA applied to initial signal timings									
Fixed Timings							9.2%	46.6%	7.8%
Actuated Timings							5.2%	1.2%	1.8%

Table 1: GLOSA Activation Frequency on Fuel Consumption.

Conclusions and future research

Objective of this paper is to evaluate performance of a GLOSA system in real-world-like simulation conditions with two sets of signal timings: fixed and actuated. The results suggest that the GLOSA application does not have an equal effect on traffic with fixed-time and actuated-coordinated signal timings, where the latter ones are collected as averages from historic records and embedded into the GLOSA algorithm. If the phase durations are predictable, as with fixed-time signal timings, then GLOSA has a significantly positive effect on stops and fuel consumption whereas its impact on travel time is miniature. However, if accurate signal timings are not known (as with actuated-coordinated signals) then it is likely that GLOSA will not bring a positive impact on arterial traffic performance. To answer few questions initiated with this research:

- Signal retiming process remains irreplaceable part of overall improvement of arterial traffic operations. With or without GLOSA, retiming of the signals brings significant benefits.
- GLOSA for actuated signals cannot bring the full benefits to practice (where actuated signals are majority) until a way is found to accurately estimate phase durations.
- Sometimes, GLOSA and similar strategies may bring more benefits than retiming of traffic signals. However, this is mostly the case with fixed-time signals where number of stops needs to be minimized.
- It seems that GLOSA brings additional benefits for signal timings which are recently retimed/ optimized. This is again the case with fixed-time signals only while the results for actuated signals are not encouraging.

Future research should address similar experiments on other networks to reconfirm results of this study or to lead to new findings. More particularly, application of the proposed methodology on a larger traffic network would further validate potential benefits. Also, research should investigate how an increase in congestion affects GLOSA and signal retiming comparisons.

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Route distribution control in road traffic networks to make on-board navigation systems become part of the traffic management

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Abstract

The paper will introduce the full chain for the centralized routing application developed within the eCoMove project for urban areas. The cooperative management of the transport infrastructure requires the provision of precise information and guidance on dedicated routes from a central knowledge base to a traveller's mobile device including navigation functionality. The traffic management is responsible for the main traffic network of the controlled area, where a traffic management control is needed to keep the traffic flowing. The onboard navigation system is responsible for the minor roads and the route to or from the controlled network, where a traffic management is not needed e.g. because of low traffic volumes. Within the major network the optimal route distribution is calculated by a neural network algorithm based on an objective function that optimises the CO_2 emissions. On request the vehicle is mapped to predefined origin and destination traffic zones. According to the route distribution matrix a route between these traffic zones is chosen. This route is sent out using the TPEG RMR (Road and Multimodal Routes) Protocol. The on-board navigation system completes the route provided by the traffic management by adding the routes within the traffic zones from its connection points to the final origin and destination.

Keywords:
ICT, ITS, eCoMove, 7th Frame program, CO_2 Emission, Traffic Management, Routing

Introduction

Algorithms that consider how to minimize travel times (or other objective functions) in a network by intelligent routing are plentiful [1]. Such algorithms are implemented within a navigation system and optimise the route of a single driver only. Navigation system recommendations contain the whole route from origin to destination.

Self-organizing, decentralized algorithms, e.g. [2], [3], [4], try to exchange data to improve network performance and prediction. They are theoretically easy to install, assuming that a certain penetration rate is reached, but fail to integrate requirements from a traffic management perspective and normally also do not arrive at a system but rather a user optimum [5]. In most cases they do not have access to detailed stationary sensor or traffic light strategies, but only to aggregated incidents like areas of congestion.

Today’s central implementations try to optimize for a system optimum, but they are not yet used to transmit this information into a navigation system. Due to the access to detailed stationary sensor and traffic light data and also future traffic management measures, like traffic light program switches, tunnel systems etc., their optimisation potential is high. But until now only variable message signs have been used. These signs are only able to cover a few routes on the major network as they can only be placed at certain decision points. As the signs show the same information to all drivers, it is not possible to balance traffic with the same O/D across several routes. For a higher effect of these signs it is also only possible to provide quite general routing information and e.g. not a detailed route.

This paper describes a full chain for the centralized routing for complex major networks, which can take into account policy objectives from a traffic management perspective. We introduce the general concept, the algorithm used for optimization and the communication between centralized traffic management and the distributed navigation systems. We also report on a study for the northern Munich area using microscopic traffic flow simulation.

General Concept

The concept is based on the distribution of the routing task between traffic management facilities and vehicles' on-board navigation systems. The traffic management facility is responsible for the major traffic network of the area managed, where a traffic management control centre has been deemed necessary to keep the traffic flowing well. Working on this basis, the on-board navigation system is responsible for the minor roads and the route to or from the managed network, where traffic management is not performed e.g. because of low traffic volumes and no need for route management.

Following the principles of traffic planning, the controlled area is divided up into traffic zones. Against the planning of a demand model [6] the only used policy to create a traffic zone is its connection to the major network. Other policies, like the structure of the traffic zones, are not used.

Policy objectives from the traffic management can be included by defining the major network – e.g. by avoiding routing through residential zones – and through the configuration of traffic zones and their connection(s) to the major network.

For the definition of the traffic zones it is necessary to distinguish between traffic zones within the controlled area and outlying traffic zones. Traffic zones within the controlled area are bordered by the major traffic network. Each traffic zone has several connection points to the major network. They are placed at the intersections. Figure 1 shows an example of possible routes between an origin traffic zone (A) and a destination traffic zone (B). The figure includes the connection points to the major network (red arrows), the advised routes from the central routing system (green), the real starting and ending position of the vehicle (yellow circle) and the part that is completed by the on-board navigation system (yellow). The central routing only takes place between these traffic zones.

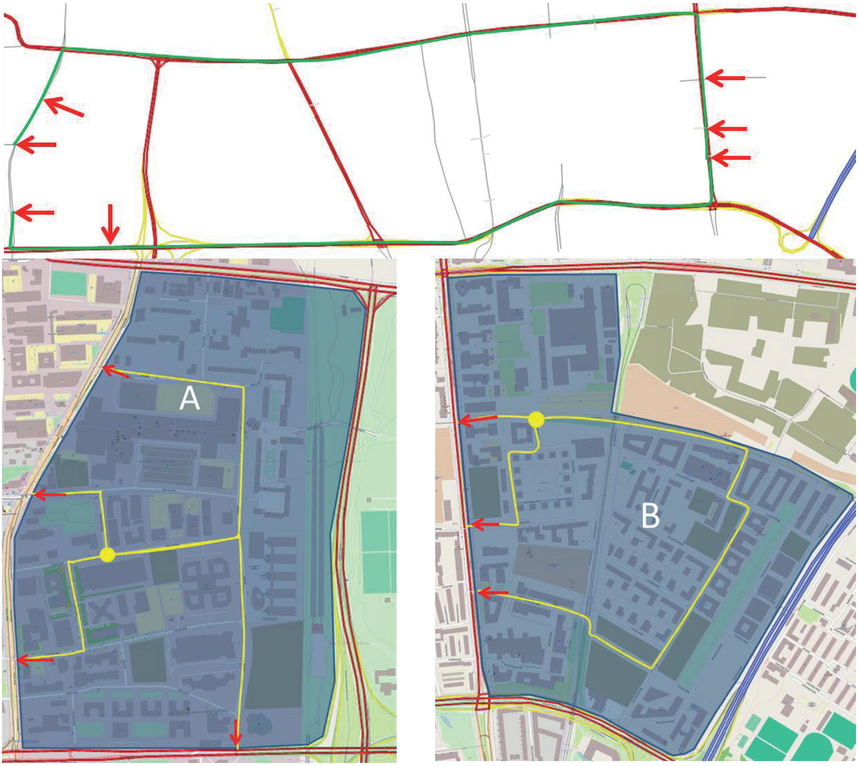

Figure 1: Example for routes between two traffic zones within the controlled area.

Every connection point of the origin traffic zone is connected to each connection point of the destination traffic zone by exactly one advised route from the central system which is optimal for the system performance. In the shown example all vehicles entering the controlled network from the two upper connection points are advised to take the northern route, whereas the vehicles entering the controlled network from the two lower connection points are advised to take the southern route. In this example there is only one route per O/D of the connection points. A distribution of the vehicles across several routes is also possible however. Depending on the exact starting and ending position within the traffic zones, the on-board system chooses the best route from the advised routes, which is chosen according to the objective function of the on-board navigation system. Due to the fact that starting and ending positions are distributed through the traffic zones, different routes will be taken through the controlled network.

Outlying traffic zones can, on the whole, be much bigger. Their size depends mainly on possible decision points in the network heading towards or coming from the controlled area.

Figure 2 shows an example for possible routes between an outlying starting position (here Karlsruhe) and traffic zone A from the previous example.

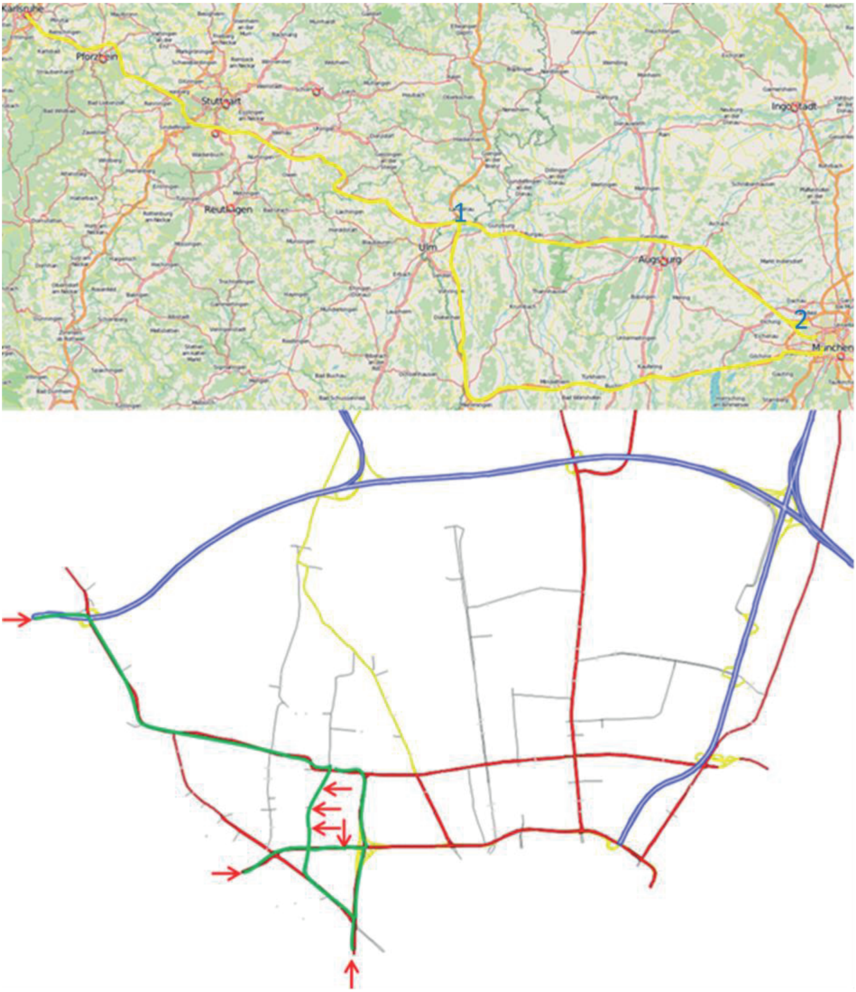

Figure 2: Example for routes between outlying starting points and traffic zones within the controlled area.

There are two ways of using the route advice service. Vehicles can (a) either subscribe to this service and receive updates on the route recommendation based on their current position and the current traffic along their route or (b) they actively request an update. Using the example shown in Figure 2, a vehicle requesting advice for a route from Karlsruhe to the centre of Munich has initially three possible connection points to the Munich traffic management area. Upon passing the motorway junction near Ulm (1) the vehicle has to make a first route choice on its way to Munich. Now it either approaches Munich from the north which restricts the access points to the controlled area to one or from the east, allowing two options (2) for connecting to a route of the controlled area. The choice between approaching Munich either from the north or from the east is based on (a) current traffic information along the major routes (yellow) and (b) traffic information and prediction for the routes advised from the central system within the controlled area (green).

System Overview

The central system consists of several components which will be described in the following sections. Figure 3 shows the system overview.

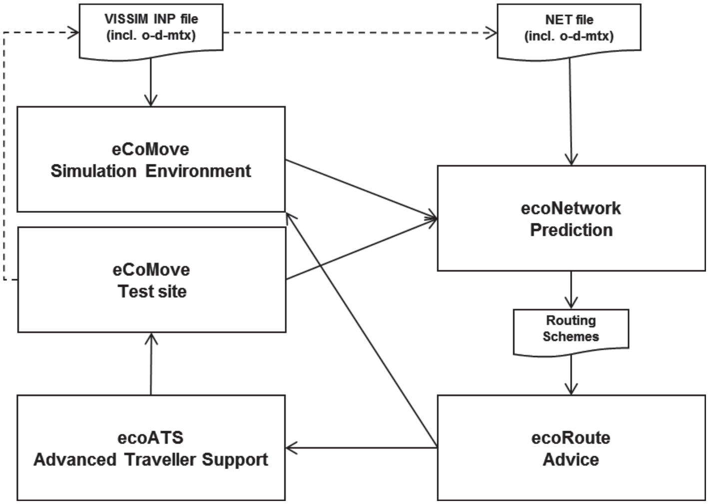

Figure 3: System Overview

The network model is derived from input data from the real test site including map and traffic light data. It is input for the simulation model as well as the 'ecoNetwork Prediction' model.

As the eCoMove simulation environment [7] allows the embedding of the eCoMove system with only a few changes the routing system can be connected to both the real test site and the simulation environment.

Desired Network State

As the service offered by the 'ecoRoute Advice' application is based on a database of current environmentally optimal routing schemes, the dynamic computation of the routing schemes on the basis of OD-matrices and dynamic TLC green time splitting rates is key.

The first step for the overall routing approach is the calculation of optimal routing schemes. This is performed by the ‘ecoNetwork Prediction’ component. It calculates the optimal route distribution within the major network (major urban roads and motorways) using a dynamic route choice and traffic assignment network model that works with a special objective function in order to optimize environmental benefit. This objective function expresses the correlation between traffic and fuel consumption and represents a strategy that reflects the system operator’s goal of minimizing the overall CO_2 emissions. The model results are time-dependent routing schemes for all origin-destination relationships in the network. The routes usually represent environmentally optimal driving though the network rather than minimal travel times. Figure 4 shows a visualisation of the desired network state.

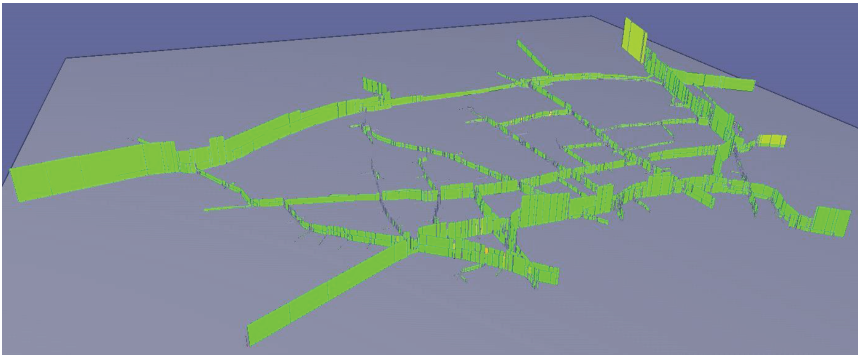

Figure 4: Visualisation traffic flows for an optimised desired network state

As the model’s task is to estimate the environmentally optimal traffic states (and not the real ones), the only dynamic data it is provided with is the averaged green time splits of the TLC signal groups. From those green splits it periodically updates its current link capacity values. Detector data and vehicle-generated data are constituted only to the current, real situation and therefore are not considered in the context of environmentally optimal modelling for the future traffic situation.

The dynamic network model for integrated dynamic traffic assignment to road networks is based on an interpretation of the road network as a special nonlinear recurrent neural network that utilises a transposed linear recurrent error-propagation network in order to very effectively determine gradients of the given objective function [8]. The first nonlinear neural network represents the dynamics of the road network with certain free parameters (intersection splitting rates) that can be adjusted permanently by the second linear error-propagation network.

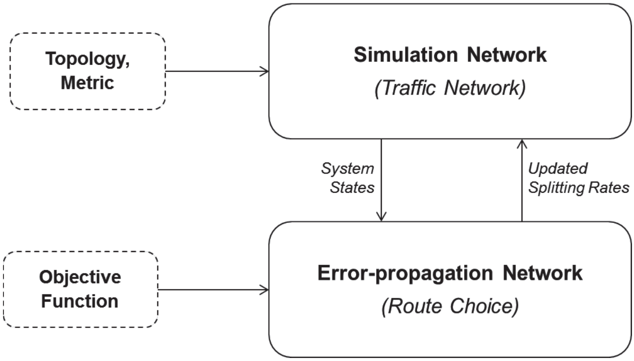

Figure 5: Two cooperating networks: The Simulation network to simulate the traffic dynamics and the error-propagation network as the controller of the first network

The note-worthy features of this dynamic network model approach are:

- The computation scheme is parallelised and can be distributed on many computation units (e.g. many processors or many processor cores).
- The simulation part of the model is capable of reproducing congestion phenomena like spill back effects.
- The error-propagation part of the model can work on almost any objective function (the only requirement on the function is that it be partially differentiable).
- It can separate any traffic subset into different layers in order to treat the traffic sub-flows differently from other ones.

The objective function uses values (i.e. gradients) that are provided by a macroscopic emission calculation that is based on a microscopic calculation [9]. The input values for the emission computation per network link are: (1) mean speed, (2) speed limit, (3) current queue length, (4) current traffic flow, (5) truck ratio and (6) road classification. The gradients are derived approximately from differences.

Route Advice

The second component, the so called 'ecoRoute Advice', is responsible for the distribution of the vehicles itself. All communication between on-board navigation systems and the central system are performed by the 'ecoATS' Service (Advanced Traveller Support), which is described below.

On request from the navigation system, the vehicle is mapped to predefined origin and destination traffic zones. Each traffic zone has at least one connection point to the major road network. According to the actual routing scheme data from the 'ecoNetwork Prediction', the 'ecoRoute Advice' chooses one route between each connection point from the origin traffic zone to the destination traffic zone.

If the traffic between two connection points is, according to the routing scheme from 'ecoNetwork Prediction', split up into several routes the one with the highest not yet served split is chosen. Therefore predicted split and desired split are compared. The difference between these splits is called the non-served split. When the on-board system navigation finally has chosen a route, this route is reserved and the non-served split for the next vehicle is adapted accordingly.

Advanced Traveller Support

The communication to the driver via the navigation system is realised by the 'ecoATS' (Advanced Traveller Support) Service. The service uses the general request mechanisms as defined in TPEG over HTTP [10]. The recommended routes are sent out using the TPEG RMR (Road and Multimodal Routes) protocol [11]. This protocol is currently under development within TISA (Traveller Information Service Association). For the transmission of route information a first draft of this future standard was investigated for the use within the eCoMove project.

Using the above mentioned ecoATS Service, the Peer-to-Peer communication scenarios are as follows:

- request of a route set fulfilling the driver's requirements,
- route choice by the driver and submission of the choice to the ecoATS Service
- update route request (a) providing information about e.g. driver's current position and (b) receiving updated route information including an update of the route

The ecoATS Service supports the same functionality for the provisioning of traffic event information using TPEG TEC (Traffic Event Compact) as well as for traffic state and prediction information using TPEG TFP (Traffic Flow Prediction).

On-board Navigation

The on-board navigation system completes the routes given by the traffic management by adding the routes within the area from its connection points to the final origin and destination. According to its used objective function of the on-board navigation system rates each route and chooses the optimal one. This route is then displayed to the driver and communicated via the 'ecoATS Service' to the 'ecoRoute Advice'.

Validation Approach

The routing has been tested in the northern road network of Munich. Due to the low number of equipped vehicles within the ecoMove project, which do not allow a useful distribution of traffic demand within the network, the validation only takes place in simulation. For this reason two traffic models are built for the test site Munich.

The macroscopic traffic model for Munich was generated out of an existing macroscopic traffic model for Germany (PTV product: Validate Germany). It includes the general network with relevant traffic demand sinks and sources. New sinks and sources were generated at all network links at the border to the surrounding, original network. The demand matrices for the Munich network were generated based on the original demand matrices for Germany. Historical loop data gathered within a previous project (Wiki [12]) from the Bayerinfo service and the city of Munich, covering a period of six months, were used as input for the calibration of the new traffic demand model for Munich using VstromFuzzy [13] as a method to adjust traffic demand between sources and sinks.

Based on the macroscopic model a microscopic VISSIM model [14] was derived and improved through detailed modelling of traffic light controlled intersections including detectors, lanes, priority rules, signal heads and real signal plans. Figure 6 shows the network used within the simulation study.

Figure 6: VISSIM model of the Munich test site

The network consists of 60 km of motorway, 100 km of urban major roads and 100 km of urban minor roads including 108 signal controlled intersections. The validation is performed for the hours of 6:00 to 12:00 of an average working day. The ratio of heavy duty vehicles for the whole network is about 10 per cent.

The validation is performed within the eCoMove simulation environment [7] through a socket connection by which dynamic TLC signal group data is provided. In response, 'ecoNetwork Prediction' writes the routing scheme data to text files that can then be used from the 'ecoRoute Advice' application to determine the optimal routes for individual vehicles. To validate the CO_2 emissions EnViVer 3.0 [15] is used.

Compared to a real implementation this has several limitations or simplifications:

- Vehicles do not have to be map matched to the traffic zones. Instead the VISSIM input link is used as a matching to the traffic zone.
- It is not possible for vehicles to change their connection point to the major network as the minor road network within the traffic zones is not part of the simulated network.

For a real network this may lead to different saturations for some links of the major road network as vehicles may enter it from a neighbouring connection point.

- The 'ecoATS Service' is replaced by the VISSIM C2X interface which influences the vehicles' routes directly.

Results

The simulation studies are carried out for the hour between 6:00 and 7:00 (total traffic demand about 43,000 veh/h) and the hour between 7:00 and 8:00 (total traffic demand about 62,000 veh/h) for penetration rates of 10, 20 and 100 per cent. The results are shown in Table 1 and Table 2. In addition, the hour between 11:00 and 12:00 (total traffic demand about 39,000 veh/h) was simulated for a penetration rate of 100 per cent. The results are shown in Table 3.

	CO_2 total per hour	NO_x total per hour	Average number of stops per vehicle	Average travel time per vehicle	Total travelled distance per vehicle
Baseline	88076 kg	439 kg	2.00	424 s	6.69 km
Penetration Rate 10%	87485 kg	439 kg	1.92	417 s	6.68 km
Decrease	0.7%	0%	4.0%	1.7%	0.1%
Penetration Rate 30%	87468 kg	448 kg	1.94	416 s	6.63 km
Decrease	0.7%	-2.0%	3.0%	1.9%	0.8%
Penetration Rate 100%	84613 kg	416 kg	2.48	434 s	6.45 km
Decrease	3.9%	5.2%	- 19.3%	- 2.3%	3.5%

Table 1: Results for the hour from 6:00 to 7:00

	CO_2 total per hour	NO_x total per hour	Average number of stops per vehicle	Average travel time per vehicle	Total travelled distance per vehicle
Baseline	113135 kg	523 kg	4.84	543 s	6.20 km
Penetration Rate 10%	112746 kg	530 kg	4.45	525 s	6.26 km
Decrease	0.3%	-1.3%	8.1%	3.3%	-1.0%
Penetration Rate 30%	113498 kg	552 kg	4.57	528 s	6.24 km
Decrease	-0.3%	-5.6%	5.6%	2.7%	0.6%
Penetration Rate 100%	108722 kg	504 kg	5.82	591 s	5.95 km
Decrease	3.9%	3.6%	-20.2%	-8.8%	4.0%

Table 2: Results for the hour from 7:00 to 8:00

	CO_2 total per hour	NO_x total per hour	Average number of stops per vehicle	Average travel time per vehicle	Total travelled distance per vehicle
Baseline	85830 kg	457 kg	1.87	403 s	6.29 km
Penetration Rate 100%	79380 kg	413 kg	3.69	426 s	5.87 km
Decrease	7.5%	9.6%	- 97.3%	- 5.7%	6.7%

Table 3: Results for the hour from 11:00 to 12:00

The results show that the system can lead to a reduction of up to 7.5 per cent of CO_2 emissions for lower traffic demands for the northern Munich network. It can also lead to a reduction of 9.6 per cent for NO_x emissions. For higher traffic demands the reduction is only up to 3.9 per cent for CO_2 emissions and 5.2 per cent for NO_x emissions.

For the number of stops the standard queue parameters of VISSIM [14] are used, which is a hysteresis defining a stop starting at a speed of 5 km/h and ending when the vehicle reaches a speed of 10 km/h. Slighter changes in vehicle speeds are only recognized within the emission calculation. The number of stops increases for high penetration rates by up to 97.3 per cent and the average travel time per vehicles increases by 8.8 per cent. Therefore there is no positive correlation between either the number of stops nor the travel time and emissions. Hence, an optimisation on travel time or stops will not lead to an optimum for emissions and fuel consumption for the northern Munich network. There is, however a correlation between travelled distance and emissions.

It is also shown that the potential for emission reduction for lower traffic demands is higher, as the demand can be more easily shifted to other roads. For lower penetration rates a positive effect on the performance indicator for traffic efficiency can be seen. For a reduction in emissions high penetration rates are needed.

Although the effect on emissions is lower for peak hour demands some additional positive effects can be seen by watching the simulation. At the end of the second simulated hour from 7:00 to 8:00 fewer queues occur in the network. Therefore a positive effect on the following hours can be expected.

Conclusion and Outlook

In this paper, we have presented a complete concept for a point-to-point, environmentally-friendly routing anywhere within a road network in cooperation with a traffic-management authority. The system works by retrieving routes within the major road network from centralized traffic management and completing these using the on-board navigation system. Real data from the road network's traffic light control can be used to estimate the most environmentally optimally routes for a network optimum. Based on these, a route distribution process is carried out centrally that assigns drivers to the various routes. Communication to the driver is achieved using the on-board device, e.g. navigation system.

In order to quantify the benefit of the system, simulation trials were carried out. Here, emissions are assessed using the Enviver3 model based on microscopic vehicle data from the simulation. It is shown that a reduction of CO_2 emissions of up to 7.5 per cent for an off-peak demand is achievable for the Munich test site.

Also this paper does not contain a business model or a strategy for introducing the system to the market, a European wide study [16] showed that drivers do not expect a big reduction of their own fuel consumption and even accept a minor increase in travel time. However, positive effects on stress levels while driving, general traffic flow and network-wide environmental-friendliness were expected by the drivers.

Acknowledgements

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Part IV: Field Operational Tests

Field Operational Test of a new Delay-Based Traffic Signal Control Using C2I Communication Technology

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Abstract

This paper presents the setup of a field operation test of a novel delay-based traffic signal control. That signal control utilizes vehicles' delay times for the green time adjustment. The delay times in this test are measured by C2I-equipped test vehicles and are transmitted to a common signal controller. The signal controller is upgraded with a road side unit (RSU). The RSU includes a communication and an application unit. The communication unit is required to receive the communication telegrams from the vehicles with their coded delay times. The delay-based control logic is executed on the application unit which is basically a small computer. The RSU is linked to the signal controller via one of the controller's standard interfaces. The utilized interface is a port which is usually used for connecting induction loops with the signal controller. The delay-based signal control sends an impulse from the RSU to the induction loop port to trigger the signal controller for a phase change. The test site is located at the non-public property of the German Aerospace Center (DLR) in the city of Braunschweig, using the facilities of the Application Platform for Intelligent Mobility (AIM). Test cases are defined to evaluate if the control logic reacts in the expected way. The overall objective of the field operational test is to prove the technical feasibility of the delay-based control by applying only standard equipment. The successful proof is the requirement for a

continuative and extensive field operational test in the public space which will investigate the control's impacts on traffic flow, waiting times and emissions.

1. Introduction

Signal control strongly influences the quality of traffic within urban street networks. For this purpose several signal control approaches have been applied in the field, trying to minimize vehicles' delay times. This is done despite the fact that these approaches cannot directly measure delay times but often use surrogate measures. Due to innovation in C2I (car-to-infrastructure) communication technology the measurement of vehicles' delay times becomes feasible in a wider scope which leads to further options in traffic signal control. Based on this progress a new traffic signal control was developed. It directly processes on-line measured delay times for signal time adjustment. This new signal timing method is completely vehicle actuated and based on an exhaustive queue clearing policy. Further details about the control method are explained in [5, 6]. To benchmark this new delay-based control several microscopic simulation studies were done, comparing the new method to conventional approaches. The simulation results were promising and showed an improved traffic flow and reduced delay times [4].

In this paper a first operational field test of the new delay-based control is described. This field test should demonstrate the technical feasibility of the new control by applying only standard equipment and a common signal controller. The impact on real traffic flow is important as well and will be investigated in a further and more extensive field operational test. In the field operational test presented here, C2I communication technology is used to transmit the self-measured delay times directly from test vehicles to the traffic signal controller. The test site is the non-public property of the German Aerospace Center (DLR) in the city of Braunschweig and the research facilities are provided by the Application Platform for Intelligent Mobility (AIM). With AIM, the German Aerospace Center, together with the state of Lower Saxony, the city of Braunschweig and other partners, is creating a unique way of linking up research, development and applications for intelligent transportation and mobility services and uses the entire region and its real traffic infrastructure as a research area [1]. On special focus in AIM is on controlling traffic signals and the delay-based signal control is a first use case.

2. Delay-Based Signal Control

For the clarification of the technical setup of the field operational test, it is necessary to briefly explain the basic control strategy of the delay-based signal control. The delay-based control requires the delay times of all approaching vehicles at an intersection for the green time adjustment. A vehicle i is considered to have a delay d_i, if its current speed v_i is below a maximum achievable speed v_{max}. This maximum achievable speed v_{max} has to be defined and could be the speed limit. The small time increment Δt between two subsequent measures depends e.g. on the frequency of the GPS readings. In this field operational test, it is required to have at least one measure every second. This is because of the simultaneous frequency of the signal controller for triggering the traffic lights. If the current speed v_i of the vehicle exceeds the maximum achievable speed v_{max}, then its delay d_i is set to 0:

$$d_i = \Delta t \cdot \left(1 - \frac{v_i}{v_{\max}}\right) \quad (1)$$

Summing up the single delay times d_i for all vehicles n results in the delay time d for the whole approach:

$$d = \sum_{i=1}^{n} d_i \quad (2)$$

Due to these definitions of the delay time, the control strategy can be explained which utilizes a queue clearing policy: Considering a fixed minimum and maximum green time (g_{min} and g_{max}), a running green phase with its already elapsed green time g is terminated, as soon as all delayed vehicles on an approach have been cleared. In this case the measured delay time d becomes less than a critical value d_{crit}. That critical value is defined close to zero to cope with detection errors. This condition for the phase change can be summarized as:

$$((d < d_{crit}) \cap (g > g_{\min})) \cup (g > g_{\max}) \quad (3)$$

The following figure 1 illustrates the delay-based control method: As soon as the delayed vehicles (red) have been cleared on the northbound approach (left), the phase is changed and the delayed vehicles on the eastbound approach (right) are served. This pattern is sequentially repeated in every cycle.

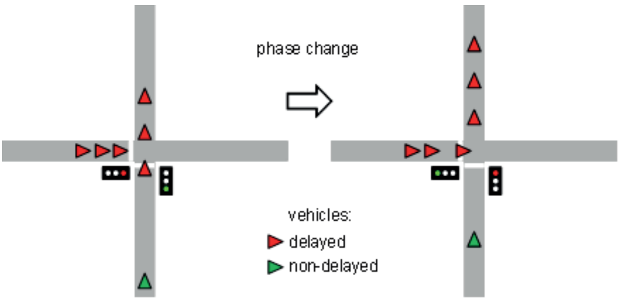


Figure 1: The delay-based signal control terminates the current green phase as soon as all delayed vehicles (red colour) have been cleared.

3. Technical Setup

To prove the technical feasibility of the new traffic signal control in a field test, the used signal controller must fulfil two basic conditions: It must be able to receive the vehicles' communication telegrams, which include their delay time states, and it must be capable to process these measured delay time states by using the delay-based logic for triggering the signals. Common signal controllers can usually not comply with these requirements. This is because of lacking interfaces for integrating novel traffic data sources into traffic signal control. Typically a signal controller only provides interfaces for connecting induction loops, infrared detectors and cameras, but no C2I communication devices. The measures of these common data sources are headways, occupancies or tailbacks and so far there was no need to process vehicles' delay times. This also means that there are no software libraries available which could handle the vehicles' delay times as an input value for setting up the new signal control logic.

The workaround to avoid these restrictions for the field operational test is to upgrade a common signal controller. A communication device for receiving the C2I telegrams and a platform for executing the delay-based signal control must be added. To get the permission for a further field operational test in the public space, it must made sure that the signal controller itself is not modified, due to safety issues. A better solution is to outsource the required functionalities to an additional device and connect this device via one of the signal controller's standard interfaces. For this purpose the already available hardware within AIM is used. Currently about 30 intersections in the city of Braunschweig are getting equipped with road side units (RSU) [2,3] to broadcast the controllers' signal states and other information for the application of e.g. a green light optimal speed advisory (GLOSA). These RSU include components for the communication with the test vehicles and a computer for processing source code [2, 3], like the control logic of the delay-based control. Until now the communication link is only unidirectional from the signal controller via the RSU to the test vehicles. For the field operational test of the delay-based control it is necessary to upgrade this link to a bidirectional communication. The communication from the test vehicles to the RSU works already but so far there is no connection to forward commands from the RSU to the signal controller.

For the following described implementations and the field operational test, a signal controller of the type series Siemens C940V and two test vehicles (so-called FASCars®) are used. This controller type in combination with a RSU is installed at most of the intersections to be regarded in AIM. The laboratory device is used to benchmark new configurations and modifications before applying them in them in the real life. Considering this the task is implementing a link from the RSU to the signal controller via one of the signal controller's standard interfaces. The used standard interface is an input port which usually connects an induction loop with the controller. The RSU is upgraded with a relay that is linked with the controller's induction loop port. The relay itself is controlled by the application unit. The delay-based signal control logic is executed on the application unit. Whenever the condition for a phase change is fulfilled, referring to (3), the relay is energized and sends an impulse to the induction loop port. The control logic executed on the Siemens C940V controller recognizes this impulse at the port. The impulse is considered to represent a vehicle passing the induction loop and causes the intended phase change. The control logic for the Siemens C940V signal controller guarantees only a fixed minimum and maximum green time and terminates a running green phase as soon as it recognizes an impulse at the port. That means in the field operational test it is only used to trigger the signals but not to execute the delay-based control logic. The setup of the signal controller and RSU is shown in figure 2.

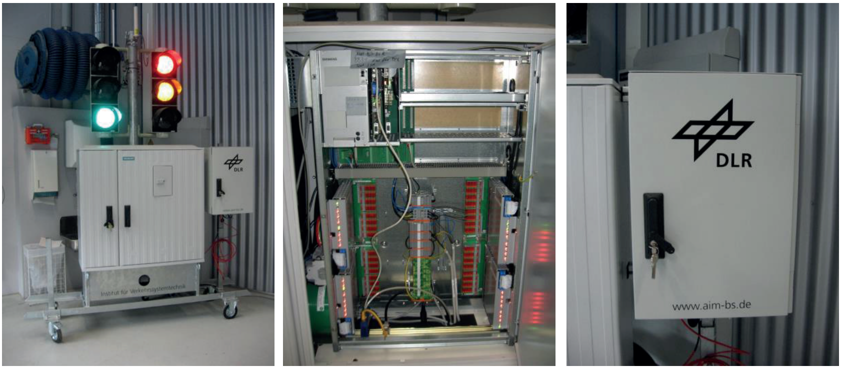


Figure 2: Field operational test installation (left) with the signal controller Siemens C940V (middle) and the road side unit (right).

To summarize the described setup for the field operational test, it can be distinguished between three major parts: The first part is the institute's two test vehicles equipped with transceivers. The second part is a road side unit (RSU) [2, 3] which includes a communication and an application unit. The third part is the traffic controller Siemens C940V which is linked to the road side unit and triggers the lights. The data exchange between these three parts is initiated by the transmission (step 1) of the self-measured delay times from the test vehicles to the road side unit's communication unit using the IEEE 802.11 p communication standard. These delay times are processed in the application unit, a Linux pc system, where the logic of the new delay-based signal control is executed. The so adjusted signal times are transmitted (step 2) to the signal controller of the type series Siemens C940V by the controller's induction loop input port to finally trigger the lights (step 3). Current status information from the signal controller back to the RSU can be received via the interface Siemens VMK. This connection from the signal controller back to the RSU is additional for logging the displayed signal states. It is not necessary for the proper functionality of the delay-based signal control. The whole system setup is shown in figure 3.

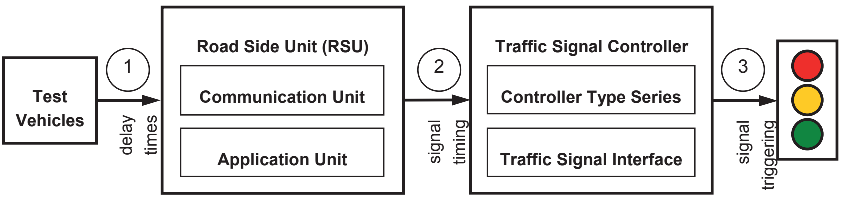
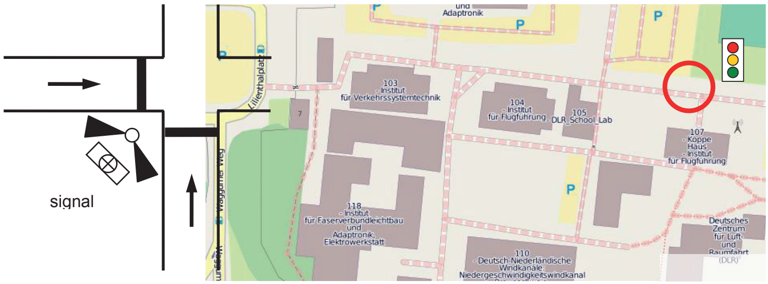


Figure 3: System setup with the used components and transmitted information. The delay times of the vehicles are received via the communication unit and are processed by the delay-based logic on the application unit. An impulse is sent from the road side unit to the signal controller's induction loop port to trigger a phase change.

At the time of writing this paper the implementation of the described system setup is still in progress: The link between the relay and the induction loop port is completed and the signal triggering logic for the Siemens C940V controller is ready for execution. Only the delay-based logic still needs to be implemented on the application unit.

4. Test Cases

The principle of the delay-based signal control can be completely tested with the available combination of the institute's one modified signal controller and the two C2I-equipped test vehicles. For the control it is not important to determine the total number of delayed vehicles. The only required information is if the sum of the delay times on an approach crosses the critical delay time value, referring to (3). That means one vehicle, with the two possible states of being delayed or non-delayed, will cause the same actuation of the control like a whole platoon. Due to these considerations the layout of the test site includes only two crossing one-way streets. These two streets form a simple intersection and are separately controlled by the signal controller's two signal groups. The location of the test site is the non-public property of the German Aerospace Center (DLR) in Braunschweig. An intersection out of the network of minor streets is chosen to install the mobile signal controller. Details about the test site are depicted in figure 4.



Source: OpenStreetMap

Figure 4: The test site is a simple intersection consisting of two crossing one-way streets, each signalized by a separate signal group (left). The intersection is located at the non-public property of the DLR in Braunschweig (right).

To prove the delay-based control and the technical setup, some test cases must be defined. These test cases must represent the most typical arrival situations at an intersection. The control logic must be able to handle all these test cases in the expected way. That means the control's basic functionalities will be tested. Essential are the green time extension until all delayed vehicles on an approach are cleared and the accuracy of the moments of phase change. To compensate the limited number of two test vehicles, the setup of the test cases distinguishes between: (A) One vehicle on each of the two approaches and (B) two vehicles on only one approach. The additional consideration of the vehicles' delay states results in 8 possible test cases: Within (A) the vehicles on both (A1), on only one (A2, A3) or on no (A4) approach can be delayed. Within (B) are the same four cases but now with two (B1), only one (B2, B3) or no delayed vehicle (B4) in a queue. Based on the order of the phases and the delayed or non-delayed vehicles, the control must act different. For example should the control extend in (B3) the running green phase until the second vehicle has passed, while in (B4) it should immediately terminate the green phase. These described test cases with different delay time states and vehicle orders are shown in figure 5 and will be tested at the equipped intersection.

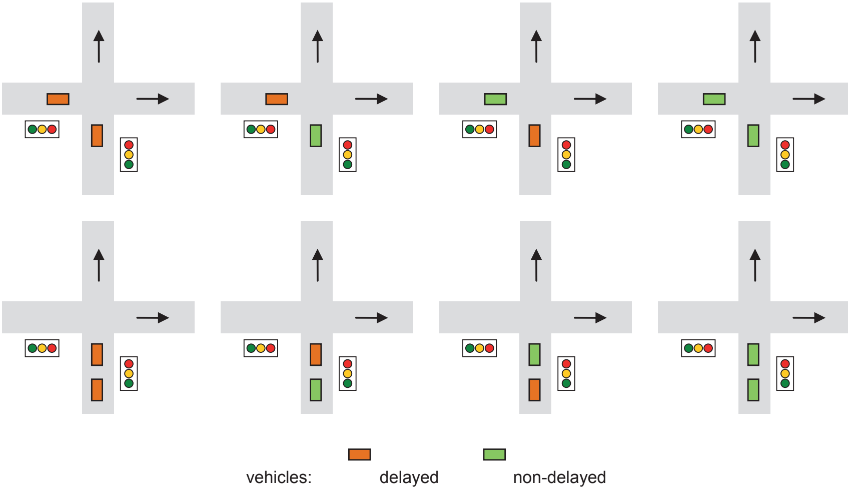


Figure 5: Eight test cases with two probe vehicles are defined: Two competing directions with one vehicle on each approach (A1-4) and one direction with two vehicles on each approach (B1-4). These test cases represent the most common combinations of delayed / non-delayed vehicles and platoons at a simple intersection.

5. Conclusions

By completing the system implementation and running the test cases, the technical feasibility of the new delay-based control will be proved. The setup of this field operational test, especially linking the road side unit (RSU) with the Siemens traffic signal controller, is in progress and detailed results will be available soon. The successful completion of this first operational test on the non-public property of DLR is the requirement for a continuative field operational test in the public space. In this second and more extensive field operational test, the impact of the delay-based approach on traffic flow, waiting times, emissions and other quality measures will be investigated.

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Characterizing Urban Travel Time Reliability along Signalized Corridors using Probe Data

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Abstract

Developing quantitative measures for urban mobility and travel time reliability is important for engineers and decision makers to prioritize capital investments, allocate operation oriented resources such as traffic signal retiming, and ultimately assess the impact of projects. A variety of data such as vehicle movement volumes, passenger movement volumes, travel time and travel time reliability can be used for assessing mobility and travel time reliability. Probe data have long been recognized as a valuable data source, but historically have been very expensive to collect large sample sets for meaningful longitudinal statistical analysis [3]. More recently, commercial probe data providers have begun offering subscription based data sets that characterize segments between freeway interchanges (uninterrupted flow facilities) and between signalized intersections on signalized arterials [4] at one minute resolution. These data are derived using crowd sourced data from applications on mobile phones, GPS devices, and vehicle telematics. This new data set provides a huge opportunity for a paradigm shift on how urban arterials are analyzed.

In this paper an 8.7-mile corridor of US 31 in Kokomo, Indiana before and after a signal retiming was analyzed using this crowd sourced data. The signalized corridor was retimed with the objective of providing good through progression as well as minimizing minor movement and side street split failures. Using one week of travel time data before the retiming and one week after, the annualized benefit of the corridor retiming was estimated to be $2.7M (U.S. Dollars). In addition, the performance of the through movement travel time through the corridor was assessed over a period 3 months prior to the retiming and 12 months after the retiming. Cumulative frequency diagrams (CFDs) were prepared for this period to assess the monthly variation in the travel time and travel time reliability. In general, the corridor exhibited only modest variations in travel time and travel time reliability. The paper concludes by summarizing the 15 months of median probe data travel times and recommends agencies integrate probe data into their assessment programs as part of a comprehensive system management and outcome assessment program.

Introduction

Modern crowd sourced data from applications on mobile phones, GPS devices, and vehicle telematics have created a new data source that is powerful for analyzing road system performance. Recently, the Indiana Department of Transportation along with Purdue University developed an Interstate mobility report using these data to locate areas where congestion occurred along interstate routes throughout the state [5]. These data provide minute by minute average speeds along over 10,000 predefined segments across the state. These segments cover both interstate and arterial routes. The use of these data has been well documented on Interstate routes, however developing a system of analytical tools to evaluate arterial performance has been a more difficult task.

Signal Retiming Evaluation

In April 2012 a signal retiming project was performed by the Indiana Department of Transportation (INDOT) on an 8.7-mile segment of US-31 in Kokomo, Indiana (Figure 1). In this retiming, 13 signals were retimed during the week of April 2, 2012 and they were fine-tuned the following week of April 9, 2012. Using the crowd sourced data, Remias et al. briefly documented this corridor using cumulative frequency diagrams from the week before the retiming and the week after the fine tuning [4]. Travel time was calculated using the minute average speeds on each of the segments over the 8.7 mile segment (Equation 1).

$$TT = \sum_{i=1}^{n} \frac{d_i}{v_i} \qquad (1)$$

Where,

n = number of crowd sourced segments
v_i = speed in miles per hour
d_i = distance of the segment in miles.

Figure 2 shows the impact of the retiming where the travel time decreased on the main line through movement for all 5 signal timing plans and both directions. Since the majority of traffic along this corridor are commuter traffic, the objective was to minimize the through movement travel time. In Figure 2, the five timing plans for both directions are shown in Figure 2d-m. The median travel time savings for all of these timing plan periods were approximately 1-minute. A 1-minute travel time savings over an 8.7-mile segment is a significant reduction that is equivalent to making it through the corridor with getting stopped at one less signal. These calculations below shows a brief assessment showing the cost of retiming the corridor can be offset by the benefit of travel time savings for 26,000 vehicles per day.

Estimated Annualized Benefits

A estimate of the user benefit of this re-timing was performed using count data and the median travel time savings. The median travel time savings for the different weekday timing plans were obtained from crowed sourced data and multiplied by the corresponding volumes during the period to calculate vehicle-hours of travel time savings. Those values were then used as input to the methodology proposed by the Texas Transportation Institute (TTI) for assessing user benefit [1].

The following equations were applied to establish a method for comparing the optimized arterial travel time (TT) to a base travel time:

$$\Delta TT = TT_{base(section)} - TT_{objective(section)} \quad (2)$$

Where,

$TT_{base(section)}$ = arterial travel time measured in minutes for a specified plan and direction running baseline offsets

$TT_{objective(section)}$ = travel time for each section, after the signals were retimed.

The cost estimation is based on the 2011 Transportation Urban Mobility Report [6]. Costs for trucks are given by:

$$User_t = \Delta TT * vol * \%T * PPV_t * \frac{\$86.81}{h} * \frac{1h}{60\ min} \quad (3)$$

Where,

$User_t$ = user cost for a commercial vehicle,

vol = volume (number of vehicles) measured for the study period,

%T = percentage of commercial trucks (4 % for weekday), and

PPV_t = number of passengers per commercial vehicle (1 for commercial trucks).

The $86.81 amount represents the commercial vehicle operating costs in 2011 dollars and is taken from the 2011 Transportation Urban Mobility Report. This value does not represent excess fuel consumption. When ΔTT is positive, the outcomes of the equation reflect a user savings. Costs for passenger cars are given by:

$$User_c = \Delta TT * vol * \%C * PPV_c * \frac{\$16.79}{h} * \frac{1h}{60\ min} \quad (4)$$

Where,

$User_c$ = user cost for a passenger vehicle,

%C = percentage of commercial trucks (96% for weekday), and

PPV_c = number of passengers per passenger vehicle (assumed 1.25).

The time value of money for passenger cars used was $16.79 per hour.

In addition to user costs, potential savings in fuel consumption and associated changes in carbon dioxide (CO_2) emissions were also derived using the formulas and assumptions from Day et al. [1]. These values can be seen in Table 1.

The results shown in Table 1 summarize the annualized benefits for system users. The savings are calculated from changes in arterial travel time measured with crowd sourced probe vehicle data and volumes are assumed using AADT and an INDOT counting station.

By retiming the US 31 corridor user cost reductions over the entire year exceed $2.7 million and a nearly 1000 ton reduction in CO2 emissions.

Signal Retiming Aging

The above calculations were performed using one week of crowd sourced data just prior to retiming and one week of crowd sourced data immediately after the retiming project was completed. However, the literature is silent on how traffic signal timing plans age and many agencies often use a 2-3 year cycle for retiming corridors. Crowd sourced data provides a cost effective mechanism for evaluating how a traffic signal timing plan ages. Understanding how a timing plan ages, can be beneficial when adapting agency standards for how often signal systems should be retimed.

Signal Retiming Aging – Weekly Analysis

Figure 3 shows 63 weeks of travel times along the US-31 corridor as cumulative frequency distributions for both directions and each of the timing plans. Each line corresponds to approximately 350 and 750 samples. The two dark lines are the original before and after CFDs that correspond to the calculated benefits summarized in Table 1, while the thinner lines correspond to the other 61 weeks. The red lines are weekly travel time summaries between Jan 1 and Mar 30, 2012 before the corridor was re-timed and the green lines are weekly travel time summaries between April 16, 2012 and Mar. 31, 2013 after the corridor was re-timed. The pattern of improvement from the 13 weeks prior to the retiming and the 50 weeks after the retiming remains relatively steady with few outlier weeks. Those outliers are not clearly understood, but most likely due to construction, crashes, severe weather, or special events.

Signal Retiming Aging – Monthly Analysis

Figure 3 suggests that weekly travel time distributions do have some outlier periods that may need to be filtered. Monthly cumulative frequency distributions may be used to provide a clearer picture of long term aging and seasonal variation trends. In Figure 4, each of the lines in the monthly CFDs accounts for between 1,500 and 3,000 travel times, depending on the length of the timing plan period. This is a significant amount of data for, especially considering a majority of before/after signal retiming studies are based on just a few probe vehicle data points from driving through the corridor [3]. Figure 4 shows the monthly cumulative frequency distributions for the three months prior to the retiming and the 11 months following the retiming (April was excluded because it was the month of the retiming). The thick lines are again the original before and after week summary from Figure 2 for context. The improvement is clear for the 11 months following the retiming of the corridor. The median monthly travel times for each of the signal timing plans are another way to visualize the improvement of the corridor and to see if there is any rebound in the plan. Figure 5 shows 15 months of median travel times for timing plan 4 (1300 – 1500) for the northbound and southbound directions of the corridor. The Southbound direction in Figure 5a has a median travel time reduction between 0.7 and 1.48 minutes. When comparing the months of March from 2012 (before the retiming) and in 2013 (after the retiming) there was a 1.16 minute reduction in travel time. This shows that over the course of the year the retiming did not show any significant aging. The US-31 Northbound median travel times showed a similar pattern of reduction in travel time in Figure 5b. The reduction in median travel time ranged from 0.62 to 1.25 minutes in the northbound direction. There was a 1.02 minute reduction in median travel time from the month of March before the retiming to the month of March after the retiming. Figure 6 shows the median travel times for both directions on all five timing plans. The reduction of median travel time pattern remains constant for both directions and each of the timing plans.

Conclusions

This data processing technique described in this paper is very scalable technique. Using minute by minute average speeds given by commercially available crowd sourced data there is potential to evaluate travel time improvements along arterial routes before and after traffic signal retimings. In the case of US-31 in Kokomo, Indiana the retiming benefits have been steady over the course of an entire year. Median monthly travel time improvements for each of the timing plans and directions remained relatively constant near one minute in travel time savings. The US-31 corridor did not show signs of substantive aging (degradation of travel time) in the year since retiming. Future research in this area will include investigating numerous arterial signal retimings over a longer period of time. This can be used to develop thresholds for identifying when signals should be considered for retiming. Also, these crowd sourced data will provide near real-time feedback to the individuals who retimed the signals.

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Part V: Generic Concepts and Visions

Driver Specific Assistance Improving Energy Efficient Driving Based on Cooperative Predictions

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Abstract

This paper summarizes the development of an Advanced Driver Assistance System (ADAS) supporting drivers to adopt efficient driving styles based on cooperative predictions. The so-called eSiM application provides predictions on upcoming driving situations and vehicle behavior. Based on these predictions different system functionalities are feasible, which are discussed in this work. The chosen system approach implements a method to ensure driver acceptance of the recommendations provided. Results obtained from validation drives with the system integrated into a test vehicle prove the approach to be viable. This finally allows the authors to give a first estimation on fuel efficiency improvements of the cooperative system as well as to point out necessary next steps in research and development.

Introduction and motivation

One major development trend in the automotive industry is the reduction of traffic-related emissions to reduce both the ecologic and economic impact of the individual and commercial mobility in future. The traffic system consists of the three elements driver, vehicle and environment offering different possibilities to reduce the demand of energy. Changes in infrastructure as well as the development of alternative vehicle propulsion systems are comparably cost- and time intensive and shall not be considered within this paper. Several studies show huge potential to reduce fuel consumption of vehicles by coaching the driver to apply a more efficient driving style [11]. Human coaches as well as technical systems are able to provide recommendations before, while or after the trip [7]. Advanced driver assistance systems (ADAS) implemented in the vehicle can support the driver to apply an anticipatory driving style avoiding the waste of energy and therefore decreasing fuel consumption. In order to come up with highly reliable and useful recommendations ADAS need to integrate information from cooperative networks in the calculations.

Integration is supposed to be one of the major trends of the 21st century as it promises solutions to cope with the progressive increase of available information both in our daily life and in industries [12]. Within the eCoMove project, carried out in the 7th framework of the European Union, potentials of integration for the automotive industry are investigated [5]. The Institute for Automotive Engineering (ika), RWTH Aachen University is a member of the eCoMove consortium and provides, among others, the ecoSituational Model (eSiM) component as an enabler for cooperative driver assistance systems (ADAS). The eSiM provides predictions of upcoming traffic situations and analyzes information from cooperative technologies [9]. The ADAS described in this paper elaborates on one possible application based on this prediction component in order to support the driver in the adaptation of more energy efficient driving styles.

Cooperative prediction of upcoming vehicle behavior in the eSiM component

The eSiM environment is a java-based application, interfacing several information sources. Primarily, static environment data based is evaluated. This information is provided by a digital map assessing the predicted most probable path (MPP). Road inclination, curvature and traffic signs (e.g. legal speed limits) along the electronic horizon together with their relative distance to the current vehicle position are passed to eSiM.

Additionally available dynamic information is added to this dataset. Vehicle-to-infrastructure (V2I) as well as vehicle-to-vehicle (V2V) communication provides additional information. Typical V2I information is provided by traffic lights for example in the cooperative network of the city of Helmond. All vehicles equipped with the eCoMove system send out V2V information and hence provide information to the eSiM. Not equipped vehicles are detected by the host vehicle's radar sensor and are also considered in the prediction.

Finally eSiM sets up a microscopic traffic simulation using the PELOPS simulation tool [2], which provides detailed models for the driver, the vehicle and the traffic environment and is developed at ika. Collected data from the mentioned sources is evaluated to virtually represent the real traffic environment. The behavior of the vehicle is simulated for the upcoming events along the electronic horizon. The eSiM calculates the resulting velocity profile, which can be used in various applications. One of these applications using eSiM prediction output is described in the following sections in more detail.

Methodology of system design based on evaluations of field operational tests

The system design is based on the evaluation of average driving behavior of subjects within a field operational test (FOT). Analysis of data from the euroFOT project [1] allows estimating the effect of different functionalities. The optimization of both the vehicle's velocity profile and its powertrain behavior is subject to various research and development projects. Deceleration situations show large potential of up to 40 % for a relative reduction of fuel consumption. Acceleration or constant velocity situations have a smaller relative potential in fuel consumption savings [4]. To identify reasonable functionalities for the ADAS, fuel consumption distribution in the FOT data is investigated according to these three driving situations and idling. The result is shown in Figure 1.

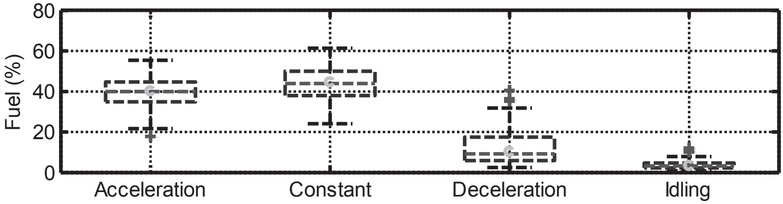

Figure 1: Distribution of absolute fuel consumption derived from euroFOT data [1]

Data is based on 93 vehicles equipped with a logging unit. A total number of 145.000 trips with a cumulated length of approximately 1.5 million km are taken into account. These values for an average driving behavior can be multiplied with the relative fuel saving potential identified in previous studies e.g. [2] and [3]. This results in an estimated fuel saving potential summarized in table 1.

Driving Situation	Acceleration	Constant Velocity	Deceleration
Fuel Share (Mean Value)	**40.16 %**	**44.43 %**	**10.14 %**
Estimated fuel-saving potential from literature [3] and simulations	10 %	10 %	40 %
Estimated saving for average driving	**4.01 %**	**4.44 %**	**4.06 %**

Table 1: FOT evaluation result and estimated total fuel consumption reduction

In conclusion, the ADAS should address all three driving situations as they offer a comparable reduction potential of about 4 % for an average driving behavior. The situations can be distinguished by the acceleration pedal position. The acceleration pedal position is the main input of the driver to control the longitudinal vehicle dynamics and therefore fuel consumption. For this reason the ADAS addresses the driver's behavior regarding the acceleration pedal usage in two ways:

- Recommendation of pedal position for acceleration and constant driving situations throughout the trip.
- Recommendation of an anticipatory early and complete release of the acceleration pedal in deceleration situations.

The adaptation of the gearbox mode enables to exploit additional reductions of fuel consumption. At ika a test vehicle is available to implement and test ADAS in real world driving. The Volkswagen Passat CC is equipped with a 3.6 l V6 engine providing a power of 220 kW and a maximum torque of 350 Nm via a 6-speed automatic dual clutch transmission. A simulation model of the vehicle's powertrain is available and can be used to predict the fuel consumption based on a given road inclination and velocity profile. Figure 2 shows both the measured (dashed) and the simulated (solid) fuel-consumption of the vehicle in deceleration situations from 50 km/h to 10 km/h for different deceleration strategies.

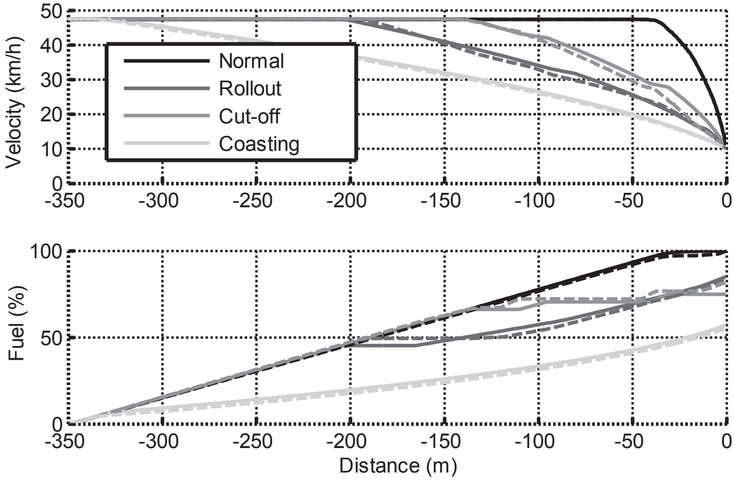

Figure 2: Velocity and fuel consumption for a deceleration from 50 to 10 km/h (dashed: measured, solid: simulated)

The dashed lines are measured values while the solid lines show the simulation results of the model. Figure 2 verifies that the model generates valid fuel consumption results. The vehicle implements four different deceleration strategies:

- "Normal" driving behavior represents a drive at constant velocity and subsequent deceleration using the conventional mechanical brake.
- "Rollout" strategy uses the standard vehicle shifting strategy. After the pedal lift-off, a partial use of the engine brake with fuel cut-off is applied. At lower engine speeds fuel is injected to the engine.
- "Cut-off" is based on the "Rollout" strategy. The implementation of early downshifts increases the engine speed, which extensifies the use of the engine's fuel cut-off mode. This results in a higher average friction torque and therefore faster decelerations.
- "Coasting" strategy is based on switching the gear lever position into neutral while decelerating. The gearbox is disengaged from the engine and therefore the engine brake torque is reduced to zero. The engine is kept at idling speed by the engine control resulting in a constant fuel rate over time.

Utility function design enabling the consideration of driver's preferences in ADAS

The different strategies shown in figure 2 are characterized by the resulting fuel consumption as well as the duration. For the application in an ADAS recommending the release of the acceleration pedal, the "entry point", characterized by the distance where the deceleration starts, has to be taken into account as well. According to figure 2, the final fuel consumption of both the “Rollout” and the “Cut-off” strategy are nearly equal while the difference compared to the “Normal” driving behavior concerning both the velocity deviation and the cumulated time varies between these strategies.

Start- and end-velocities are viable criteria to distinguish deceleration situations. The deceleration strategies described before result from the vehicle’s’ driving resistances and the powertrain behavior. The road inclination is available in digital maps and is therefore taken into account.

The huge variety of several situations and several driving strategies requires an approach to identify the strategy that suits best for the driver. This results in a multi objective decision process. The criteria influencing the driver’s decision are the cumulated fuel consumption as well as the cumulated time compared to the average driving behavior [10]. A utility function to identify the strategy with the highest scalar utility value for drivers is designed as given in equation 1.

$$u = k*w*\Delta E + (1-w)*\Delta t \qquad (1)$$

In this equation Δt and ΔE represent the increase in time and the reduction in fuel consumption of an efficient alternative driving strategy compared to the average behavior. The factor w represents a weighing factor allowing the driver to configure the system behavior. The utility function is parameterized by the factor k, defining the scalar relation between fuel consumption reduction and duration increase.

To parameterize the ADAS for deceleration situations, the simulation model is used to simulate a set of different decelerations. The following parameters are varied:

- Start-velocity (15 to 130 km/h in steps of 5 km/h)
- End-velocity (10 to 125 km/h in steps of 5 km/h)
- The average road inclination (-4 to 4 % in steps of 0.4 %)

The fuel consumption, duration and strategy for each manoeuvre relative to the basic strategy (“Normal”) are stored. Figure 3 visualizes the simulation result as a distribution.

This distribution shows a Pareto front representing optimal combinations of a maximum fuel consumption reduction with a minimum increase in travel time. The utility function shown before results in lines of equal utility in this diagram. The inclination of these constant utility lines is adapted by the weighing factor w. If w is zero, the fuel consumption is not considered in the utility function. Consequently this results in horizontal lines with the highest utility at minimum time increase. A value for w of 1 is represented by vertical lines with the highest utility at the maximum fuel consumption decrease. The Pareto distribution can be determined for all situations and operating strategies. For each situation, a bandwidth of possible strategies is available, defined by the most time- and the most fuel-efficient strategy. Two examples in this figure visualize this for single situations. The number of strategies for these situations exceeds the three alternatives “Rollout”, “Cut-off” and “Coasting” as they are also combined with the “Normal” strategy. These combined strategies take the partial usage of the vehicle brake at the end of the deceleration into account. This avoids premature decelerations below the target velocity due to inaccurately estimated driving resistances (relevant for real world test runs). To get a comparable system behavior for all situations the factor k is calculated by averaging the bandwidths of strategies for all simulated situations.

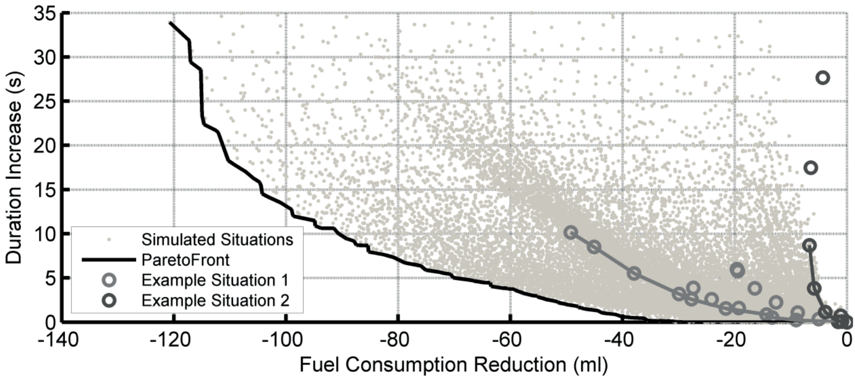

Figure 3: Simulated combinations of fuel consumption reduction and duration increase

Additionally the total utility function considers short-term deviations in velocity of the optimized compared to the reference or “normal” velocity profile. The evaluation of the behavior of several drivers reveals an average deviation of human driver’s velocity choices in uninfluenced deceleration situations. This average deviation defines the maximum tolerated deviation for optimized trajectories compared to the reference. The utility function furthermore accounts a minimum duration to avoid frequent switches of the gearbox mode, which is not in the scope of this paper.

To reduce computational effort in the implemented ADAS, a multi-dimensional array is derived from the simulations described above. Usage of the inputs average inclination on the road ahead, weighing factor w as well as the start- and end- velocity allows accessing the results of the simulations. Based on these inputs the array provides the distance when a recommendation has to be issued as well as the corresponding gearbox operating strategy as an output. Figure 4 gives an excerpt of this matrix.

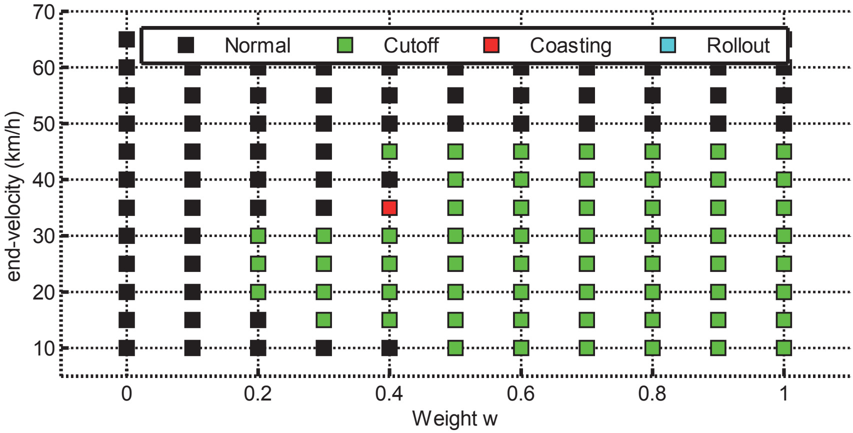

Figure 4: Strategies with highest utility (inclination: 0 %; start velocity: 65 km/h)

The operation modes suggested for a start-velocity of 65 km/h and an inclination of 0 % are given for different end-velocities. The strategy with the highest utility varies between the different deceleration situations. Velocity differences between start- and end-velocity of 15 km/h or below result in the choice of the “Normal” strategy. No recommendation is derived as the duration of alternative strategies is shorter than the defined minimum duration for a change in the gearbox operating strategy. For high values of w, the “Cut-off” mode dominates other strategies for this specific start-velocity and road inclination. In figure 5 the matrix content is evaluated for all deceleration situations regarding the influence of the weighting factor w.

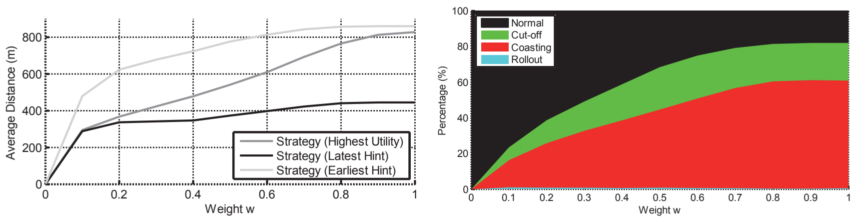

Figure 5: Distance to issue a recommendation and selected strategy depending on w

The evaluation reveals for a weighting factor w of zero that the ADAS always selects normal driving. For a weighting factor w of 1 the strategy coasting provides highest utility in 60 % of the deceleration situations. This complies with results visualized in figure 2 as the coasting strategy realizes the highest fuel consumption reduction. Furthermore the analysis points out that the average hint distance increases with an increasing w. This is depicted in the left diagram and also corresponds well with figure 2 as the coasting strategy requires the longest distance.

In acceleration situations nearly infinite possibilities to shape the velocity profile according to different optimization criteria exist. There are no reproducible discrete trajectories as they exist for deceleration situation, which requires a different approach. Thus the ADAS considers acceleration situations by recommendation of a pedal value limit to avoid harsh accelerations.

Implementation of the system and the Human Machine Interface

The integration of the ADAS in the test vehicle requires the development of a human machine interface (HMI). As the system immediately addresses the driver's control of the vehicle, it is preferable to display the relevant information close to the drivers normal view direction (e.g. in a head-up display). Outputs in the test vehicle are limited to the central display in the console as well as to acoustic signals. A 3D mouse, originally designed for CAD applications, enables a user input. The final test setup in the car is shown in figure 6.

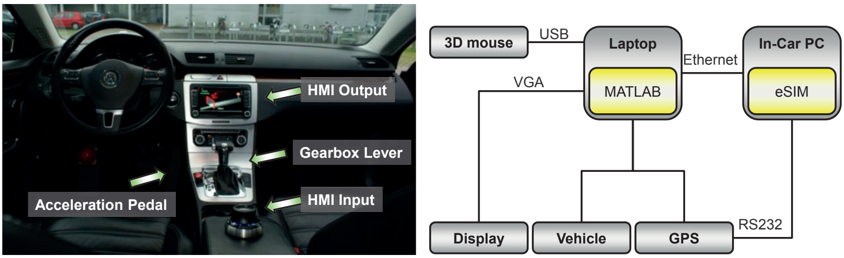

Figure 6: Photo and scheme of the hard- and software architecture

The resulting soft- and hardware architecture in the test vehicle is shown in the right hand side diagram of figure 6. The ADAS is implemented using the Real Time Windows Target, a toolbox for the Simulink software based on MATLAB. This toolbox allows to run a real-time application in windows, which is required for the communication with the vehicle, and to interface other components using Ethernet, USB and VGA connections. The visualization of a HMI can be implemented using the 3D animation toolbox in MATLAB.

Within the Simulink model the input data provided by eSiM, the vehicle and the human machine interface (HMI) is read-in and processed to the control strategy. A set of three possibilities is given to the driver to configure the system behavior. First, drivers can adjust their preference whether they prefer to apply the most efficient driving style or a normal driving without a lost in time. This is represented by the bar shown in the middle of figure 7.

Figure 7: Driver setting options of the ADAS

A value of 10 represents a weighing factor w of 1 to look up in the matrix described above. On the left hand side, the second setting possibility is shown. It allows the driver to choose between a purely recommending system behavior and a semi-autonomous system, which automatically changes the gearbox mode according to the driver's reaction. Finally, the graphics to the right show one of seven available options for the driver to choose the style of the system's feedback according to his driving. Although a feedback is especially necessary for systems coaching the driver, the optimal style of the feedback varies according to the driver's motivation [8]. Thus drivers can choose between a symbolic representation (e.g. flowers) and a direct feedback (e.g. the fuels' price in Euros saved by applying the systems recommendations).

The deceleration assistant analyses the PELOPS prediction generated with eSiM according to upcoming deceleration situations and stores the end-velocities. The current vehicle velocity is considered as the start-velocity. The average inclination along the distance to the next deceleration events is calculated. These values are fed into a look-up function based on the array described above. The function returns the strategy with the highest utility for this deceleration situation, based on the driver-set weighting factor w. The strategy is defined by the distance to release the acceleration pedal is as well as the corresponding gearbox mode. Considering this distance, a virtual distance point ahead is determined where the recommendation has to be given. The gearbox mode is stored and eventually applied after a driver's reaction.

When the vehicle approaches the identified virtual point of the acceleration pedal release, a state machine is used to coordinate the system behavior. The graphical output dynamically switches as shown in the figure 8.

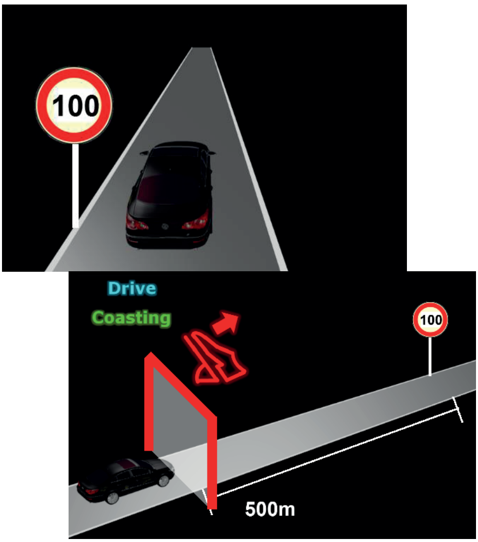

Figure 8: HMI output for free driving (left) and deceleration (right) situations

The left figure shows the graphical layout while driving freely. The relevant driving situation given by eSiM (e.g. the legal speed limit) is presented. During a deceleration situation, the view changes and provides further information, as shown in the right figure. Both the reason for the deceleration and the current distance to this event are shown in the upper right corner. Meanwhile a virtual "gate" is approaching, representing the determined virtual position of the acceleration pedal release. If the driver obeys the recommendation, defined by a pedal position of zero, within a given time period this gate changes its color from red to green. Afterwards, the driving strategy shown in the upper left corner is selected, either automatically or by the driver depending on the chosen setting. A missing driver reaction first leads to an acoustic signal and finally results in pure information about the upcoming deceleration event.

The second system functionality addresses the pedal position while driving freely (acceleration or constant velocity situations). A vertical bar is shown to the driver. The bar given in figure 7 is arranged right to the virtual road in the left perspective of figure 9.

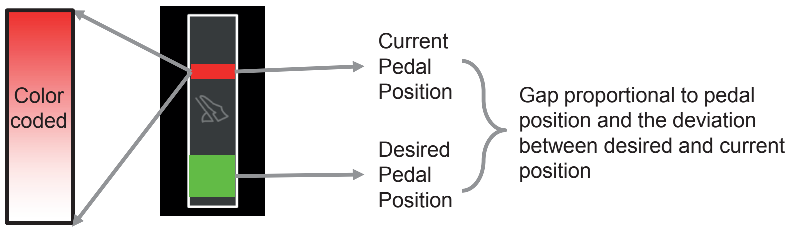

Figure 9: Additional HMI output for free driving situations

The bar represents possible acceleration pedal positions between 0 and 100 %. Additionally the current pedal position is visualized as a thin horizontal bar and a target pedal position value is defined, using a thicker green bar. When the driver exceeds the legal speed limit or a maximum pedal position, the current pedal position changes from white to red color whereas the desired target pedal position lowers. The sensitivity of this behavior is affected by the drivers weighing factor w and supports the driver in travelling at efficient speeds without harsh, inefficient accelerations.

System validation in real-world test drives

Real world driving tests in the vicinity of the city of Aachen are carried out to proof the functionality of the system. First, the system behavior is examined in a deceleration situation given in figure 8.

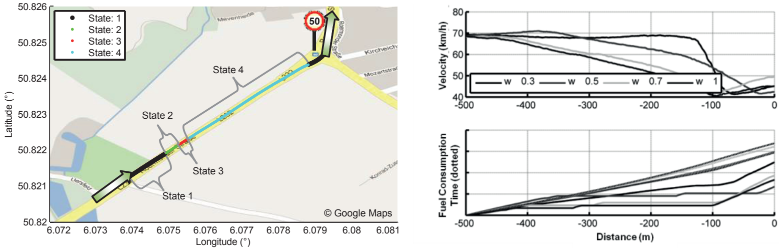

Figure 10: Location and measurement results for a deceleration situation

On the left hand side the deceleration situation is shown as a plot of the GPS signal as well as the system states, representing the state machine mentioned in the section before. When the driver approaches the speed limit, the system identifies the deceleration and returns the recommendation (state 2). After the drivers' reaction (state 3) the deceleration strategy is applied (state 4). The right diagram compares test runs with different weights w for this situation. For a weight w of 0.5, 0.7 and 1 a "cut-off" strategy is applied whereas for a weight of 0 and 0.3 no recommendation is provided. This complies with the matrix given in figure 4. The right diagram in figure 10 reveals a fuel saving potential in the deceleration situation of 35 % for all weighting factors w, compared to a "normal" driving with standard deceleration and application of mechanical brakes.

Based on this validation of the system functionality in deceleration situations, the fuel saving potential is investigated for a complete driving cycle. The evaluation of the systems effect on fuel efficiency in acceleration and constant velocity situations is included into the comparison of total fuel consumption for the representative cycle. Therefore test drives are performed on the "Aachener Runde", a 26 km long combination of both urban/motorway (10 km) and rural driving (16 km) in the vicinity of the city of Aachen as given in figure 11.

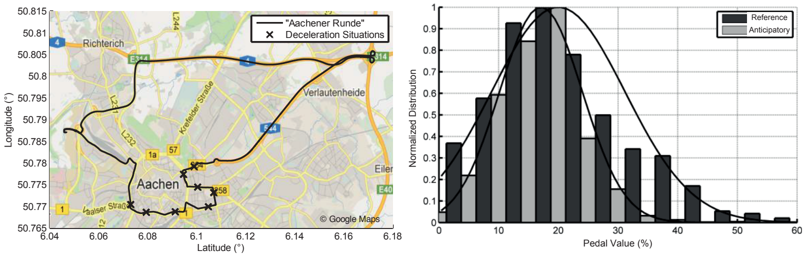

Figure 11: Location and measurement results for the test cycle

The crosses in the left figure mark situations with the system issuing recommendations on upcoming decelerations. All of these situations are located in the urban part of the driving cycle and are related to traffic lights. This results from the comparably large velocity gap between the start- and the end-velocity of the deceleration (from approx. 50 km/h to a stop). The diagram to the right shows the normalized distribution of pedal values of both test runs. Both the mean value and the standard deviation are lower for the anticipatory driven test run (with a weight factor w of 1) compared to the reference drive. This is caused by the permanent recommendation of a pedal value as described before. Table 2 summarizes the results for both a reference drive with the weight factor w turned to 0 and the same result with a factor w of 1.

"Aachener Runde"		Typical [5]	Reference	Anticipatory
Weight w		-	0	1
Average speed	(km/h)	-	38.06	39.46
RPA urban	(m/s²)	0.233 – 0.269	0.237	0.159
RPA rural	(m/s²)	0.129 – 0.167	0.130	0.078
RPA combined	(m/s²)	-	0.166	0.105
Fuel Consumption	(%)	-	**100**	**83.8**
Travel Time	(%)	-	**100**	**96.5**

Table 2: Numeric results for the test cycle and typical values according to [5]

The Relative Positive Acceleration (RPA) is used to evaluate both runs with respect to driving behavior. This indicator describes the dynamics of a velocity profile and helps to distinguish between the driving styles "eco", "normal" and "sportive" [5]. In the reference test for both urban and rural parts the RPA values are within the typical and average range defined in [5]. Hence the identified reductions in fuel consumption are representative for normal and average drivers. The system reduces fuel reduction by 16.2 % on this reference course. The average speed of the anticipatory driven test run is slightly higher compared to the reference test and therefore travel time is reduced by 4.5 %. The consideration of V2X information is expected to yield further fuel reduction potential. V2I information on signal phases of traffic lights allows the deployment of anticipatory decelerations without increasing travel time. Hence this helps to increase driver acceptance and avoids periods of idling. V2V information on vehicles in front is similarly useful to reduce idling or mechanical braking.

Conclusion and outlook

This paper summarizes the design approach for an ADAS issuing recommendations for a more fuel efficient driving style to drivers. The system design bases on the investigation of large-scale FOT data and the characteristics of the test vehicle considered in this work. A utility function models driver's preferences and allows emphasizing fuel efficiency or travel time demand by variations of a weighting factor. The impact of different driving strategies such as "Rollout" or "Coasting" on this utility is assessed in simulations for a variety of different situations. A multi-dimensional array containing information on the strategies providing highest utility is derived for different values of the weighting factor, representing different preferences of the driver. The resulting look-up table contains the distance in front of a traffic light or speed limit that requires the driver to release the acceleration pedal. Additionally eventual changes in the gearbox operating strategy are available in the table.

The applied method adapts the system behavior to the driver's preferences, which is represented by a weighting factor, to ensure driver acceptance. Recommendations are derived from a pre-calculated multi-dimensional array in order to reduce calculation demand in the vehicle. The system as well as the HMI are implemented using real-time capable hardware and are integrated in the test vehicle. First test drives proof system functionality and reveal a fuel reduction potential of up to 16 % for a combined test cycle in and around the city of Aachen. The system relies on the predicted velocity profile, which is derived by microscopic traffic simulations in the eSiM component. The evaluation of various information sources enables the eSiM to fully exploit cooperative information from communication technologies. Consequently the ADAS approach presented is able to consider cooperative information in the recommendations.

Two aspects of the described systems are currently subjects for ongoing research. First of all driver acceptance of efficient deceleration strategies needs to be elaborated in more detail. A driving simulator study is carried out to investigate the driver's preferences and driver acceptance of deceleration recommendations. This study can be extended to real world driving tests using the implemented ADAS. In a second step the cooperative aspect of the system using V2X information needs to be validated accurately. Several traffic lights in the city of Aachen are currently being prepared to send out V2I information. Furthermore onboard devices are set up to test V2V functions. This can improve the quality of the velocity profile prediction and thereby the quality of the recommendations provided by the system.

Acknowledgements

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