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Development and application of a methodology to estimate the CO_2 emissions from transportation

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The example of a household based inventory

Master's thesis

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Abstrakt

Um dem Klimawandel vorzubeugen ist eine Reduzierung der CO_2 Emissionen dringend notwendig. Verkehr, als einer der Hauptverursacher dieser Emissionen, muss bei jedem umfassenden Ansatz zur Vermeidung des Klimawandels miteinbezogen werden. Während bundesweite Emissionsinventare des Verkehrs eine lange Tradition in Deutschland haben, sind personen- oder haushaltsbezogene CO_2 Emissionserfassungen nicht im gleichen Maße berücksichtigt. Eine Analyse der bestehenden Modelle ergab, dass kein Modell verfügbar ist, welches auf einer individuellen Ebene eingesetzt werden kann und alle verkehrsbezogenen Emissionen in einem well-to-wheel Ansatz miteinbezieht. Aufgrund dieses Mangels an passenden Optionen, wurde ein neues Modell entwickelt, welches die verkehrsbezogenen CO_2 Emissionen eines Haushalts unter Einbeziehung der direkten „heißen“ und „kalten“ Emissionen und der Emissionen der Kraftstoffvorkette berechnet. Neben den konventionellen Antriebsarten des Straßenverkehrs ist auch eine Option für ein Elektroauto vorgesehen. Schienenverkehr wurde aufgrund der angestrebten Verwendung des Models für den ländlichen Raum nicht berücksichtigt. Grundlagedaten für dieses Modell sind die Emissionsdatenbank HBEFA und die Bibliothek für Lebenszyklusdaten ProBas. Die Programmierung des Modells mit drei Detailierungsgraden wurde mit VBA Makros in Microsoft Excel realisiert. Das Ergebnis wird als Menge der transportbezogenen CO_2 Emissionen pro Haushalt und Zeitraum ausgegeben. Zusätzlich zum Modell wurde auch ein Fragebogen entwickelt um das Sammeln der nötigen Eingangsdaten zu gewährleisten und somit eine umfassende Methodik zur Bestimmung von verkehrsbezogenen CO_2 Emissionen zu gewährleisten. Eine Sensitivitätsanalyse ergab, dass Reisedistanz und Besetzungsgrad der Fahrzeuge die wichtigsten Input Parameter für das Modell sind. Als weitere einflussreiche Parameter identifiziert werden konnten die Qualität der tank-to-wheel Daten, der Hubraum, das Verkehrsmittel und die Verkehrssituation für das detaillierteste Modell. Als beispielhaftes Anwendungsszenario für die entwickelte Methodik wurde das laufende Forschungsprojekt sun2car in Garmisch-Partenkirchen ausgewählt. Da zum Zeitpunkt der Abgabe, noch keine empirischen Mobilitätsdaten vorlagen, wurde ein generischer Datensatz entwickelt. Mit einer CO_2 Emission von 17.505 Gramm pro Haushalt und Tag für ein durchschnittsdeutsches Mobilitätsverhalten, liegt das Ergebnis in einem realistischen Rahmen. Zusätzlich wurden verschiedene Maßnahmen zur CO_2 Emissionsreduzierung getestet. Die Einführung eines Elektroautos resultierte in einem moderaten CO_2 Einsparungspotential während eine Erhöhung des Besetzungsgrad und eine Verringerung des Hubraums sich als sehr effektiv erwiesen. Die Tests und eine abschließende Evaluierung ergaben, dass die entwickelte Methode geeignet ist um die verkehrsbezogenen CO_2 Emissionen eines Haushalts im ländlichen Raum zu erfassen. und die Wirksamkeit von CO_2 Reduktionsmaßnahmen abzuschätzen.

Abstract

To prevent climate change a reduction of CO_2 emission is urgently required. Transportation as one of the main contributors to these emissions has to be considered in every comprehensive approach to climate change prevention. While nationwide emission inventories of transport have a long tradition in Germany, person- or household-related CO_2 emission inventories are not considered to the same extent. An analysis of existing models showed that no model is available which can be used on a micro-scale and which covers all transport-related emissions in a well-to-wheel approach. Due to this lack of suitable options a new model had to be developed estimating traffic-related CO_2 emissions of one household. "Hot" and "cold" direct emissions are considered as well as the emissions of the preliminary energy chain. The considered propulsion technologies are the conventional ones and an additional option for an electric vehicle. Rail transport is not considered due to the intended application of the model to a rural area. Basic data for the developed model was retrieved from the HBEFA database and ProBas, a collection of lifecycle data. The programming of the model with three levels of detail was realized with VBA macros in Microsoft Excel. The output is given as the amount of transport-related CO_2 emissions per household and period. In addition to the model a questionnaire was designed to make the collection of the needed input data possible. This way a comprehensive methodology to estimate transport-related CO_2 emissions was developed. A sensitivity analysis showed that the most important input parameters for the model are the trip length and the occupancy rate of the vehicles. Further parameters the model showed to be highly sensitive to are the quality of the tank-to-wheel data, the cubic capacity, the transport mode and, for the most detailed model, the traffic situation. As an exemplary application scenario for the developed methodology the currently ongoing research project sun2car in Garmisch-Partenkirchen was chosen. Since at the time of hand-in no empirical mobility data was available, a generic dataset was designed. With a CO_2 emission value of 17,505 grams per one household and day for a German average mobility pattern, the result lies in a realistic range. Additionally to the average situation, different CO_2 reduction measures were tested. The implementation of an electric car showed moderate CO_2 saving potential, while an increase of occupancy rate and a decrease in cubic capacity for the private vehicles proved to be the most effective measures. The tests and a final evaluation showed that the methodology is suited for assessing the transport-related CO_2 emissions of a household in a rural area and is furthermore a practical tool to analyze the effectiveness of CO_2 reduction measures.

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Abbreviations

ART	Swiss Federal Research Station Agroscope Reckenholz-Tänikon
ARTEMIS	Assessment and Reliability of Transport Emissions Models and Inventory Systems
CNG	Compressed Natural Gas
COPERT	COmputer Program to calculate Emissions from Road Traffic
COST	European Cooperation in Science and Technology
DB	The German railroad company (*Deutsche Bahn*)
E85	ethanol gasoline mix (85% ethanol, 15% gasoline)
ECE	Economic Commission for Europe
eLCAr	E-Mobility Life Cycle Assessment Recommendations
EMPA	Swiss Federal Laboratories for Materials Science and Technology (*Eidgenössische Materialprüfungs- und Forschungsanstalt)*
EPF Lausanne	École Polytechnique Fédérale de Lausanne
ETH Zurich	Swiss Federal Institute of Technology Zurich (*Eidgenössische Technische Hochschule Zürich)*
GAP	Garmisch-Partenkirchen
GEMIS	Global Emission Modell for Integrated Systems
GHG	GreenHouse Gas
GIS	Geographic information systems
GPS	Global Positioning System
IINAS	International Institute for Sustainability Analysis and Strategy
JRC	European Research Center of the European Commission
KBA	Federal Motor Transport Authority (*Kraftfahrt-Bundesamt*)
KOMOD	*Konzeptstudie Mobilitätsdaten Österreichs*
KONTIV	*Kontinuierliche Erhebung zum Verkehrsverhalten*
LCA	Life Cycle Assessment
LPG	Liquefied Petroleum Gas
M85	methanol gasoline mix (85% methanol, 15% gasoline)

MEET	Methodologies for Estimating air pollutant Emissions from Transport
MiD	Mobility in Germany (*Mobilität in Deutschland*)
MiT	Mobility in Tables (*Mobilität in Tabellen*)
MOP	German Mobility Panel (*Deutsches Mobilitätspanel*)
MOVES	Motor Vehicle Emission Simulator
NEDC	New European Driving Cycle
PHEM	Passenger Car and Heavy-duty Emission model
ProBas	*Prozessorientierte Basisdaten für Umweltmanagement-Instrumente*
PSI	Paul Scherrer Institute
TREMOD	TRansport EMission MODel
TRENDS	TRansport and ENvironment Database System
UBA	German Environment Agency (*Umweltbundesamt*)

1. Introduction

"This is a crisis. A threat to us all. Our economies. Our security. And the well-being of our children and those who will come after….We must take ownership. We, collectively, are the problem."

Secretary-General of the United Nations Ban Ki-Moon at the Climate Change Conference Doha 26/11/2012 – 08/12/2012 (United Nations 2012)

1.1. Context and problem definition

The scientific evidence of the warming of the Earth's climate is mounting. The IPCC Fifth Assessment Report Climate Change 2013 states: "Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, sea level has risen, and the concentrations of greenhouse gases have increased." (IPCC - Intergovernmental Panel on Climate Change 2013) Even though the exact connections between increased greenhouse gas emissions and climate change are still not fully understood, it becomes more and more evident that this connection does exist.

Carbon dioxide (CO_2) is by far the most important greenhouse gas with a percentage of 87% of the overall greenhouse gas emissions. Most CO_2 emissions arise from fossil fuel combustion in industrial plants and engines. 18% of the CO_2 emissions in 2011 are allocated to transportation and out of this share 95% is due to road transport. (Umweltbundesamt 2013)

There is no doubt that actions have to be taken to lower the total CO_2 emissions. Due to its high contribution every approach to climate change prevention can only be comprehensive with putting a major focus on transportation.

Measures to reduce CO_2 emissions are numerous: reductions of motorized travel, shifting travel to less energy-intensive modes or changing fuel and engine technologies.

One way for the Federal Government to decrease CO_2 emission is by putting thresholds for CO_2 on new passenger cars. In a step by step implementation the limit value is 120 g/km in 2015 and 95 g/km in 2020. For light duty vehicles the values are 175 g/km and 147 g/km respectively. (Umweltbundesamt 2013)

But as Ban Ki-moon stated, ownership has to be taken at every level. To lower greenhouse gas emissions by 40% until the year 2020 (compared to 1990), the target level declared by the Federal Government, acting on the national level is not sufficient (Bundesministerium für Umwelt 2013). Measures at the community level have to be considered to change daily life decisions of individuals. With traffic being a big contributor to CO_2 emissions a shift in individual mobility behavior is essential.

One approach in this field is currently being investigated within the sun2car project in Garmisch-Partenkirchen, a showcase for electric mobility which started in fall 2013. The sun2car research project is a cooperation between AUDI AG, the Research Center for Energy Economics and the

Technical University of Munich, represented by the Chair of Urban Structure and Transport Planning and the Institute of Automotive Technology. 20 households will take part in the study. Prerequisite of the proband households is that they live in a one-family house that is equipped with a photovoltaic system, so solar energy is available. 10 households received an A1 e-tron electric car, the other 10 households received a conventional car, to be able to serve as a control group. Six months the mobility of the probands will be tracked with GPS-capable smartphones then the proband groups switch cars for another six month. During this time the following aims are pursued:

- Analysis of holistic electro-mobility concepts
- Development of Smart-Grid-concepts
- Definition of requirements for intelligent charging solutions
- Information of citizens and raising their awareness for CO_2 emissions and CO_2 neutral mobility in everyday life

The Technical University of Munich is mainly involved in the latter work package, analyzing the probands' mobility behavior and corresponding CO_2 emissions. Furthermore the probands are informed through a smartphone app about their individual CO_2 balance and suggestions of measures of how to improve it are made. This information is expected to positively influence the proband's mobility behavior. The magnitude of this influence is and the possibilities of CO_2 emission reduction that arise from this tool will be assessed. (Technische Universität München & Forschungsstelle für Energiewirtschaft 2012)

Different tools to estimate CO_2 emissions of traffic have already been developed in Europe and abroad; most of them, however, focusing on large scale inventories. Household based CO_2 inventories, which are needed to assess emissions of individual mobility behavior, on the other hand have not been considered in research to the same extent (Grischkat 2008).

1.2. Objective of the work

The aim of this Master's thesis is to give an overview of the existing models and to develop a suitable methodology to estimate CO_2 emissions from transport that can be applied to the micro-scale level of one household. The methodology should cover the construction of a CO_2 emission model as well as the design of survey documents to collect data to feed the model.

The methodology should be developed in a way that it can be applied to the sun2car project but is suitable for other applications as well. This will mean that apart from conventional transport modes, an electric car option has to be designed as well.

The results, additional to being a transport emission inventory, should hold information necessary to analyze the most influencing parameters. This way the model can be used to assess the effectiveness of different emission reduction measures. Furthermore the results could be used to inform the probands about their individual CO_2 emissions and thus raise their awareness for environmental friendly mobility decisions.

Particular attention will be paid to the adaptability of the methodology to a wide range of applications as well as a simple handling and low costs for software requirements and data collection.

1.3. Structure of the thesis

The thesis starts out explaining some basic principles on emission estimation (chapter 2). Furthermore material flow concepts are introduced to describe different product system boundaries for the emission estimation. For all concepts the most important parameters are identified to give an overview of the factors that have to be taken into consideration for the development of a comprehensive methodology.

In a next step the overall system boundaries are defined to determine the scope of the work (chapter 3). This step serves to identify the specific requirements of the research question in order to guarantee the development of a suitable methodology. The desired output for the model is defined by the functional unit. Temporal and geographical scope are determined as well as transport modes and mobility activities considered. Furthermore a fitting material flow concept is chosen to be able to cover all necessary emissions. Finally the level of detail and the coverage of the input data are discussed. With these specifications the following literature analysis is structured.

The literature review (chapter 4) is then carried out to identify the current state of research on CO_2 emission estimation. Focusing on emission models in Europe, the state of the art is ascertained and the most appropriate sources for delivering the needed emission data are selected. Additionally, methods to collect mobility data are investigated as well as mobility surveys carried out in Germany to decide on a suitable mobility data collection approach.

With the collected information a first draft of the model structure is completed, followed by the construction of a database in Microsoft Excel (chapter 5). Using emission factors from different sources a detailed data basis is created, covering all parameters identified to be of importance. With the help of VBA (Visual Basic for Applications) programming, the emission factors are connected and dimensioned to the desired outcome. The user interface is presented and the basic calculations are explained. Furthermore the reader receives instructions on how to read the results and how the model can be expanded for different or more specific uses. As a last point in chapter 5 survey documents are designed with the software tool Evasys. These documents help to collect all necessary data to feed the model.

In a sensitivity analysis (chapter 6) the model is tested showing how influential the different model parameters are to the final output. This analysis helps to identify which parameters might have to be revised due to their importance. Furthermore it gives information on how exact the input data should be (where specific values should be used rather than averages) and where measures to reduce CO_2 emissions would be most effective.

To show how the methodology for CO_2 emission estimation is applied the research context of the sun2car project is used (chapter 7). Due to the status of the project at the time of preparation, no empirical data was available. From publicly available sources a generic dataset is constructed and the results for this input data are calculated. Applying different scenarios the effectiveness of different measures to lower CO_2 emissions is estimated.

In a final evaluation (chapter 8) the strengths of the developed methodology are highlighted and some weaknesses are identified. Consequently a need for further research is discussed. The findings of the thesis are summed up in chapter 9 followed by a conclusion and an outlook on potentials of household based CO_2 inventories.

2. Theory on CO_2 emissions from transportation

With CO_2 emissions from transportation being a large contributor to the global greenhouse gas (GHG) emissions, emission estimation is a well-researched field. To provide a theoretical basis for the following work, some basic principles for emission estimation are discussed helping to identify the important parameters that have an impact on the outcome. This information will serve as guidance for the following model construction ensuring that all key factors are taken into account.

2.1. Basic principles of emission estimation

Emissions from transportation can be generally described with the following equation (Technische Universität München 2013):

$$E = EF \times A$$

E: Emissions from transportation

EF: Emission factor

A: Activity intensity

The emission factor is normally stated as the amount of pollutant per vehicle kilometer. For the here analyzed pollutant CO_2 the unit of the emission factor is normally stated as g CO_2/veh-km. The emissions considered depend on the scope of the emission estimation.

The activity intensity describes the amount of vehicle kilometers per functional unit (the unit of the desired output that all data is dimensioned to). Depending on the scope of the emission estimation (nationwide inventories down to person based inventories) the activity intensity covers the travel data of one nation or one person. The thesis presented here aims to estimate the transport related CO_2 emissions for one household, thus the desired outcome would be grams of CO_2 per household and day. For this case the activity intensity would be the following (Technische Universität München 2013):

$$\frac{veh\_km}{household \times period} = \frac{persons}{household} \times \frac{trips}{person \times period} \times \frac{pers\_km}{trip} \times \frac{veh\_km}{person\_km}$$

This activity intensity depends on the case specific mobility data such as:

- km travelled per functional unit
- persons per household
- the ratio between vehicle kilometer and person kilometer which can be estimated from the occupancy rate and the number of seats of the vehicle as shown below

$$\frac{veh\_km}{person\_km} = \frac{veh\_km}{persons/vehicle} = \frac{veh\_km}{occupancy\ rate\ [\%] \times \frac{number\ of\ seats}{vehicle}}$$

How the data on activity intensity can be collected will be discussed later on in this thesis, as this information will be the input data for the developed model. The following paragraphs will discuss what influences the emission factor and which parameters are of importance to ensure a correct CO_2 emission assessment.

2.2. Material flow concepts

Traditionally in emission factor estimations only the direct CO_2 emissions are taken into account, which occur during the combustion process in the engine. In the recent decades, however, this approach has been identified as insufficient for a comprehensive analysis of transport emissions. CO_2 being a globally active GHG, the question arises of how to treat the CO_2 emissions that come up during the production and disposal processes that are necessary to provide one vehicle kilometer. To be able to do so, material flow concepts, commonly used to describe production processes, are applied (Foley et al. 2011). Depending on the drawn system boundaries the following approaches have been developed (Figure 1).

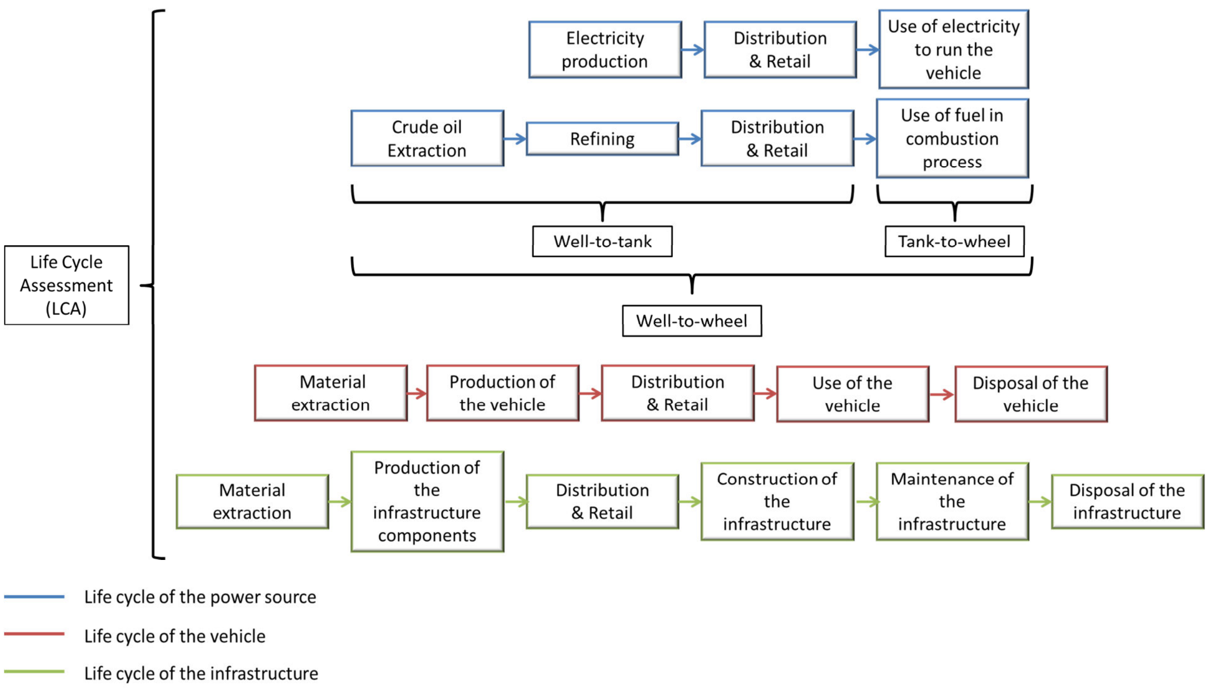


Figure 1: Material flow concepts

The tank-to-wheel approach has the smallest scope. Only the direct emissions resulting from the burning of the fuel in the vehicle engine are taken into account. This means that transport modes that run on electricity are not considered, due to their emission-free use phase. This type of estimation is used for GHG inventories on big scales. It is the most commonly used approach, since it is simple and little time consuming.

The well-to-wheel approach, as the name implies, goes further back until the extraction of the fuel. All the emissions resulting from every process step from the extraction over transportation until the use of the fuel in the vehicle are considered. These preliminary energy chain emission values can be found in literature and are expressed in grams of emissions per liter/certain amount of energy content of fuel.

Finally there is a lot of research carried out to comprehensively estimate the overall emissions of transportation. To do so the whole life cycle is included. Meaning, apart from the well-to-wheel emissions also the production of the car, the infrastructure, the maintenance etc. contribute to the total CO_2 emissions. The detail of the life cycle assessment (LCA) depends on the goal and scope definition of the respective LCA. Due to the large amount of data requirements, this type of analysis is mainly carried out for specific micro-scale situations.

No matter which of the presented approaches is applied, the resulting emission factors depend on a large number of different parameters. To ensure a complete CO_2 emission estimation within this thesis all important parameters that influence the emission factor are identified.

2.2.1. Tank-to-wheel

To analyse the tank-to-wheel emissions, first a closer look at the combustion process is crucial. The commonly used combustion engines run with either diesel or gasoline. Both are mixtures of different hydrocarbons. Next, the combustion process will be presented in a simplified form using the least complex hydrocarbon methane (CH_4) as an example. In a complete combustion process the chemical reaction is a simple oxidation which looks as follows (Bornitzky 2010):

$$CH_4 + 2\ O_2 \rightarrow CO_2 + 2\ H_2O$$

This process assumes a perfect fuel/air ratio. In the case this ratio is not ideal the following reactions occur:

$$2\ CH_4 + 3\ O_2 \rightarrow 2\ CO + 4\ H_2O \text{ (air deficit)}$$

$$CH_4 + 3\ O_2 \rightarrow CO_2 + 2\ H_2O + O_2 \text{ (excess air)}$$

Whether or not this combustion process will be complete depends on the engine as well as every chemical reaction on the ambient conditions, such as temperature and altitude.

Assuming a complete combustion, the emission factor is solely linked to the type and the amount of fuel needed to provide one vehicle kilometer. The detailed parameters that influence this amount can be roughly divided into the following categories:

- Engine characteristics
- Vehicle characteristics
- Ambient conditions (temperatures, road gradients)
- Driving behavior

The engine characteristics define which type of fuel is used in the combustion process. Depending on the fuel type the engine efficiencies are slightly different. With a value of around 35% for example, the efficiency of diesel is higher than the gasoline value around 28%. (Aral Forschung)

Certainly an important role is played by in the vehicle itself. Three resistances influence the fuel/electricity consumption (Guzzella 2010):

- The air resistance, which is defined by the frontal surface of the vehicle (A_f) and a coefficient describing the aerodynamics (c_w)

- The rolling resistance, determined by the vehicle mass (m) and a coefficient of rolling friction (c_r)
- The acceleration resistance defined by the vehicle mass (m)

Depending on how much power is needed the engine has different cubic capacities, describing the volume swept by all the pistons inside the cylinders of the engine.

Also the auxiliary consumers in the vehicle are of importance. The lights, air conditioning or seat heaters need energy to run, which increases the fuel consumption again. With the example of air conditioning it becomes clear that the use of auxiliary consumers is dependent on the time of year. Ambient temperatures highly influence the extent of use.

This leads to another factor influenced by ambient conditions which is cold start emissions. Research has shown that if a fully cooled engine is started, the emission levels and the fuel consumption are higher than in the case where it is being warm from operation. This is due to lower engine and ambient temperatures, which result in higher frictional losses of the engine and incomplete catalytic effects. With petrol engines furthermore, a higher enrichment of the air-petrol mixture contributes to this effect. These additional emission factors are considered to be significant which is why ambient temperatures and parking times should be included in the assessment as well. (Umweltbundesamt, INFRAS & ifeu - Institut für Energie- und Umweltforschung Heidelberg GmbH 1999)

A factor which is often not considered but influences driving behavior and emission levels is the road gradient. A vehicle driving uphill consumes more fuel than on a flat road, due to the gravitational force increasing. Driving on downgrades on the other hand, leads to lower consumption rates as the gravitational force favors the vehicle. Since the emission of CO_2 is directly linked to the fuel consumption the same conclusions apply for the emission values. One might speculate that the increased energy and emission rates uphill will be offset by the lower rates downhill. As research has shown, however, this does not apply to reality (Boriboonsomsin & Barth 2009; Harris 2004). Several papers have shown that the relationship between fuel consumption and road gradient is not linear but rather parabolic (Boriboonsomsin & Barth 2009). The results of Boriboonsomsin and Barth which are displayed in Figure 2 show this relationship.

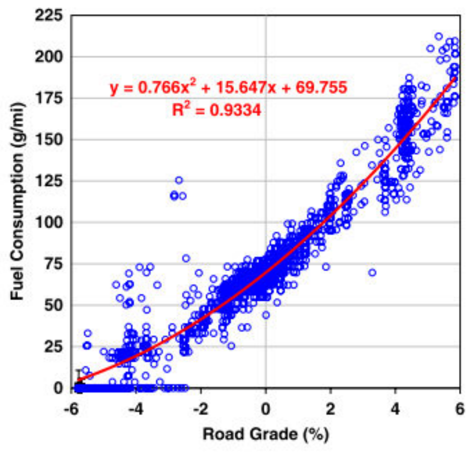


Figure 2: Fuel consumption versus road grade for steady speed of 60 mph (Boriboonsomsin & Barth 2009)

Retrieved from the figure, between the range of -2% and +2% only the relationship was identified to be linear, which means that the emissions of ascending and descending vehicles would balance each other for road gradients between -2% and +2%. These findings coincide with other literature values (Harris 2004). If the gradient value is higher than 2% the emissions are higher than they would be with the same vehicle on a flat road. Comparisons of the fuel economy between two routes of different road gradient characteristics have shown that the fuel consumption of the flat route is 15% to 20% lower than the fuel economy of a hilly road. This difference being significant, road gradients should not be neglected in the emission estimation process.

Finally the driving cycle highly determines the fuel consumption. The driving cycle displays the speed over time. This way acceleration and breaking processes can be determined. This driving profile is defined by the individual driving behavior (passive, aggressive), the street type including speed limits and the level of service (traffic jam, free flow). To estimate emissions and fuel economy in passenger cars a widely used approach is to use a standard driving cycle. In Europe the official standard is the New European Driving Cycle (NEDC). Below is a depiction of how this driving cycle looks (Figure 3).

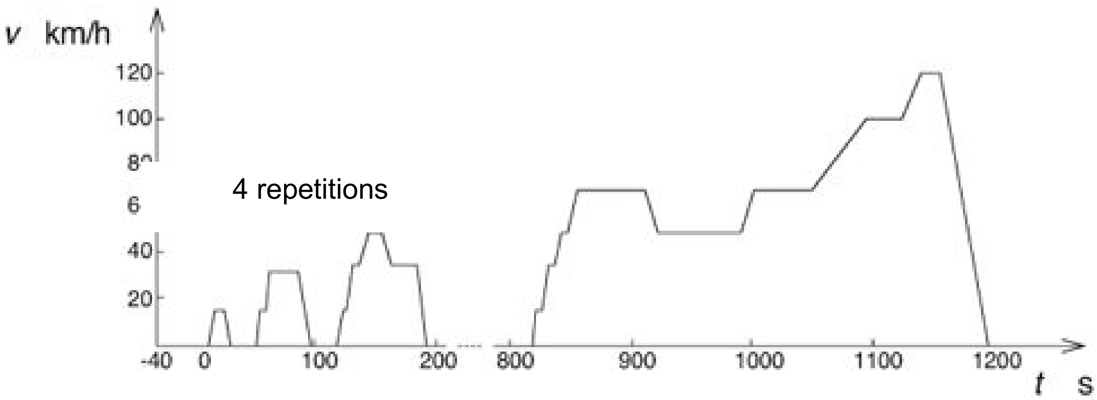


Figure 3: New European Driving Cycle (Guzzella 2010)

The mechanical energy to move the vehicle within a NEDC can then be estimated with the following, simplified equation (Guzzella 2010):

$$E \approx A_f \times c_w \times 19{,}000 + m \times c_r \times 840 + m \times \frac{11\ kJ}{100\ km}$$

Thanks to direct correlations of energy consumption and CO_2 emissions, the emissions could be thus estimated very easily. The NEDC, however, is highly criticized for being too “soft”, meaning that in reality speeds and accelerations are significantly higher which leads to an increased fuel consumption (Guzzella 2010). To ensure a realistic emission estimation a more detailed approach is needed. This topic will be further discussed in chapter 4. So far electric vehicles have not been considered due to the absence of CO_2 emissions during the use phase. This however does not mean electric modes of transport are completely emission free. The well-to-tank emissions discussed in the next chapter are of importance for all vehicles.

2.2.2. Well-to-wheel

While tank-to-wheel emissions only occur for fuel based vehicles, the well-to-tank emissions are also important for "emission-free" modes of transport such as electric cars and electrically powered trains. Together they form a well-to-wheel approach. The well-to-wheel emission estimation includes the production of the power source (fuel or electricity). Every litre or kilowatt hour of the power sources has embedded CO_2 emissions, including all CO_2 emissions during the life cycle of the power source. To estimate the total amount, the consumption values per vehicle kilometre are crucial. The fuel or electricity consumption is dependent on the same factors as the well-to-wheel emissions, also valid for electric modes of transport such as rail/electric vehicle. Below a simplified life cycle for the power sources is shown (Figure 4).

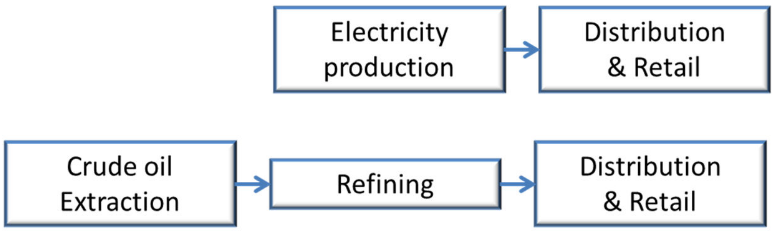


Figure 4: Life cycle of the power source in transportation

Important parameters for the quantity of well-to-tank emissions are:

- Type of power source (gasoline, diesel, electricity etc.)
- Production process
- Production location (leading to different transport distances)

Depending on the power source type, the production differs in energy intensity. For the mineral oil fuels, the fuel type determines the number of steps in the refining process, leading to different amounts of energy needed to produce the same amount of fuel. But even for the same type of fuel the production processes can be very different, depending on the production practices within the individual production sites. For the electricity production this is even more important, as there are numerous production possibilities for the same end product (one kWh electricity). Possible electricity sources are coal-fired power stations, nuclear power stations or renewable energy power sources such as wind or solar energy.

A significant influence on the well-to-tank emissions has furthermore the location of the production. While fuels have to be transported with energy intensive processes, for electricity overcoming large distances means power losses.

All these steps in the life cycle of the power source lead to CO_2 emissions. These have to be allocated to the final power source unit which is needed to provide one vehicle kilometer.

(Joint Research Center of the European Comission, Institute for Enviornment & Sustainability 2010; Chester, Horvath & Madanat 2010)

2.2.3. Life cycle assessment

For a complete LCA of a vehicle kilometer, the approach is similar to the well-to-wheel approach, only this time not only the fuel but all other components that are necessary to provide one vehicle kilometer are included. These components are the vehicle itself and the infrastructure the vehicle is using. The life cycle of the vehicle is shown below (Figure 5):

Figure 5: Life cycle of a vehicle

The first three steps of the life cycle of the vehicle are similar to the fuel life cycle. Even though the vehicle production is a lot more complex (a car for example consists of more than 10,000 different parts Zellner 2010) the basic parameters influencing the final emissions are the same. The material of the end product, the production process and the transport distances are essential. Unlike the fuel, however, the car is not used up but has an average lifetime of around 8.7 years (Kraftfahrt-Bundesamt KBA 2013). During this time the car has to be maintained and parts have to be replaced. After the use, the car then has to be disposed and recycled. All these steps are contribute to the overall life cycle CO_2 emissions.

Depending on how deep the LCA goes, the infrastructure (streets, rails, airports) is also taken into consideration. An exemplary life cycle of an infrastructure is shown below (Figure 6):

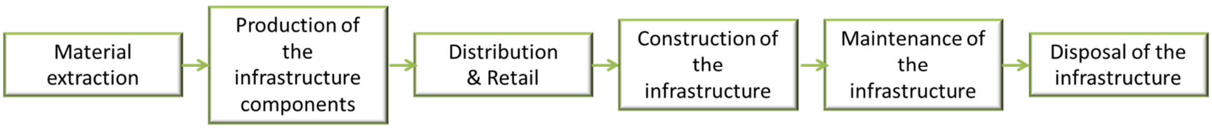


Figure 6: Life cycle transport infrastructure

Same as the vehicle life cycle, the maintenance of the infrastructure and the disposal are of importance.

Clearly a full LCA of one vehicle kilometer may become rather complex depending on the desired level of detail. The number of parameters that influence the LCA CO_2 emissions are endless, thus only a rough overview was given.

(Joint Research Center of the European Commission, Institute for Environment & Sustainability 2010; Chester, Horvath & Madanat 2010)

2.3. Summary of the theory chapter

This chapter gave an overview of the basic principles of emission estimation, identifying two main information blocks needed: information on activity intensity and the emission factor. Data on the former will be collected individually for each case, for the latter a data basis has to be constructed.

Depending on the applied material flow concept the number of parameters influencing the CO_2 emissions from transportation differs. From the most simple tank-to-wheel approach the complexity rises when it comes to well-to-tank emission estimation and even more for a LCA. As shown above, the necessary data to estimate emission factors is overwhelming, depending on the drawn system boundaries. To narrow this data down to a manageable amount, the following chapter will define the system boundaries for the specific intended application of this thesis.

3. Definition of the system boundaries

As shown in the previous chapter (chapter 0) an all-embracing emission estimation is highly complex and might be impossible for the desired level of detail. To ensure a model of manageable complexity and meaningful results the scope of the emission estimation should be adapted to the specific research question.

In contrast to the prevailing practice of estimating CO_2 emissions in nationwide inventories, the focus of this research question is on a micro scale inventory. The emissions of households as the basic economic and social unit are investigated to demonstrate the magnitude of emissions on the micro scale level and to show how behavior changes can influence the environmental impact.

To define the scope the following aspects are discussed:

- Environmental effect
- Functional unit
- Material flow concept
- Transport modes
- Geographical scope
- Temporal scope
- Mobility activities
- Parameters considered for the direct emissions

3.1. Environmental effect

The focus of this project is set on the CO_2 emissions caused by transportation. This is due to transport being one of the main contributors to GHG emissions and the fact that the model is designed to be used in projects that estimate what effect the knowledge about the personal emissions has on the individual mobility behavior. CO_2 as the predominant greenhouse gas produced by transport is well known to the wider public and the emission expected to have the biggest influence on mobility behavior. Other pollutants will not be considered, which will keep the model slim and clear. However, the methodology will be developed in a way that it can be used for other pollutants and GHG as well.

3.2. Functional Unit

A functional unit is defined to provide a reference to which the inputs and outputs can be related. The functional unit of this model is: “to estimate the transport related CO_2 emissions for one household for a user defined period”. The resulting unit of the output, as discussed in chapter 2.1, will be:

$$\frac{grams\ of\ CO_2}{household \times period}$$

To be able to analyze the CO_2 emissions within the family furthermore the emissions per household member as intermediary results are of interest. The unit for this output is:

$$\frac{grams\ of\ CO_2}{person \times period}$$

The period will not be further specified; rather that decision is left to the user. Due to the intended level of detail, investigating every single trip, the period should not exceed one week.

3.3. Mobility activities

This study is aiming at developing a tool to estimate individual mobility behavior. The focus will be on everyday mobility where the individual makes choices every single day. The nature of this research question leaves out the topic of holiday traffic. How this subject is of great importance for a complete transportation-CO_2 balance is shown in a study carried out by Holz-Rau and Sicks (Holz-Rau & Sicks 2013). Their findings show that holiday trips despite their low occurrence have a significant effect on the total traffic demand and due to their high fuel consumption also a high impact on overall CO_2 emissions. This fact has to be kept in mind, when looking at the results calculated by the here developed model. A completely comprehensive CO_2 emission calculation for individual transportation would have to take holiday traffic into account which would lead to higher total values.

While private trips and the corresponding choice of mode of transport can be directly influenced by the individuals, working trips are mostly predestined and thus cannot be influenced easily. The tool developed here is supposed to be used to investigate impacts of mobility behavior changes, which is why focusing on the influenceable part of the mobility behavior is justifiable and working trips thus are excluded.

3.4. Transport modes

Since the model will be used in order to investigate how the knowledge about transport-related CO_2 emissions will influence individual mobility behavior of a private household, only passenger transport will be considered. Freight transport will be excluded from the assessment. The passenger transport modes modeled will be, first, the conventional car for individual transport. Furthermore the option of an electric car will be included. As a further mode of motorized private transport motor bikes will be part of the assessment, as a first estimation of the used transport modes in GAP has shown that they are frequently used.

The non-motorized modes, walking and cycling, are part of the mobility pattern, however, are not of importance for the CO_2 emission estimation since both modes do not produce CO_2 within a well-to-wheel estimation. Thus they will not appear in the model. To analyze and interpret the results, information on these modes of transport, however, is crucial. In the mobility data collection they hence have to be considered.

As for public transportation, the decision was made to exclude rail transport from the assessment. This was done to save substantial modeling effort which will ensure a more detailed analysis of the remaining modes of transport. For the here presented example GAP it is expected that the local public transportation only consists of public busses. This will lead to a certain limitation of the model to rural areas or small towns, due to time issues this has to be accepted.

Air craft will not be taken into account, since it is not expected to be a mode of transport for the everyday life

These assumptions thus narrowed down the modes of transport considered for the model to passenger cars (conventional and electric), motorcycles and urban busses.

3.5. Material flow concept

As discussed in chapter 2.2, different boundaries for the emissions considered can be defined. To decide which approach is most suitable the concrete example of sun2car will serve as a guideline. The different system boundaries for the specific problem presented in this study are depicted in the following two figures, which show the system first with the conventional car only (Figure 7) and then with the electric car (Figure 8).

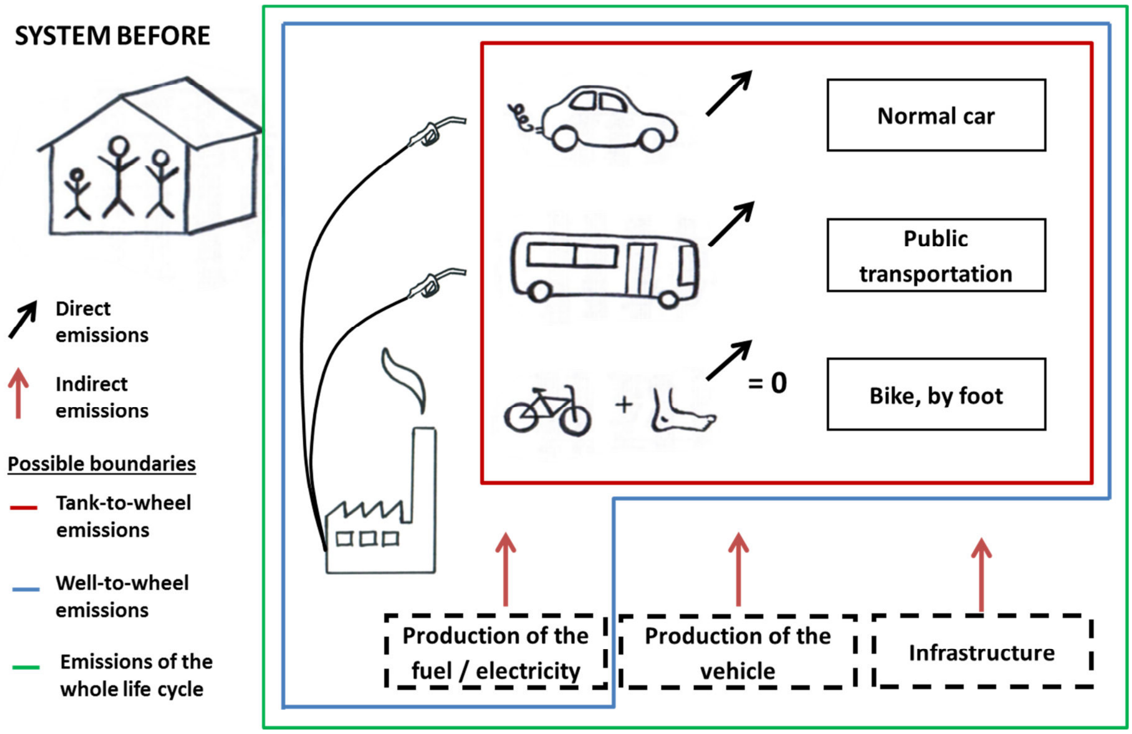


Figure 7: System boundaries for the CO2 emissions without the electric car

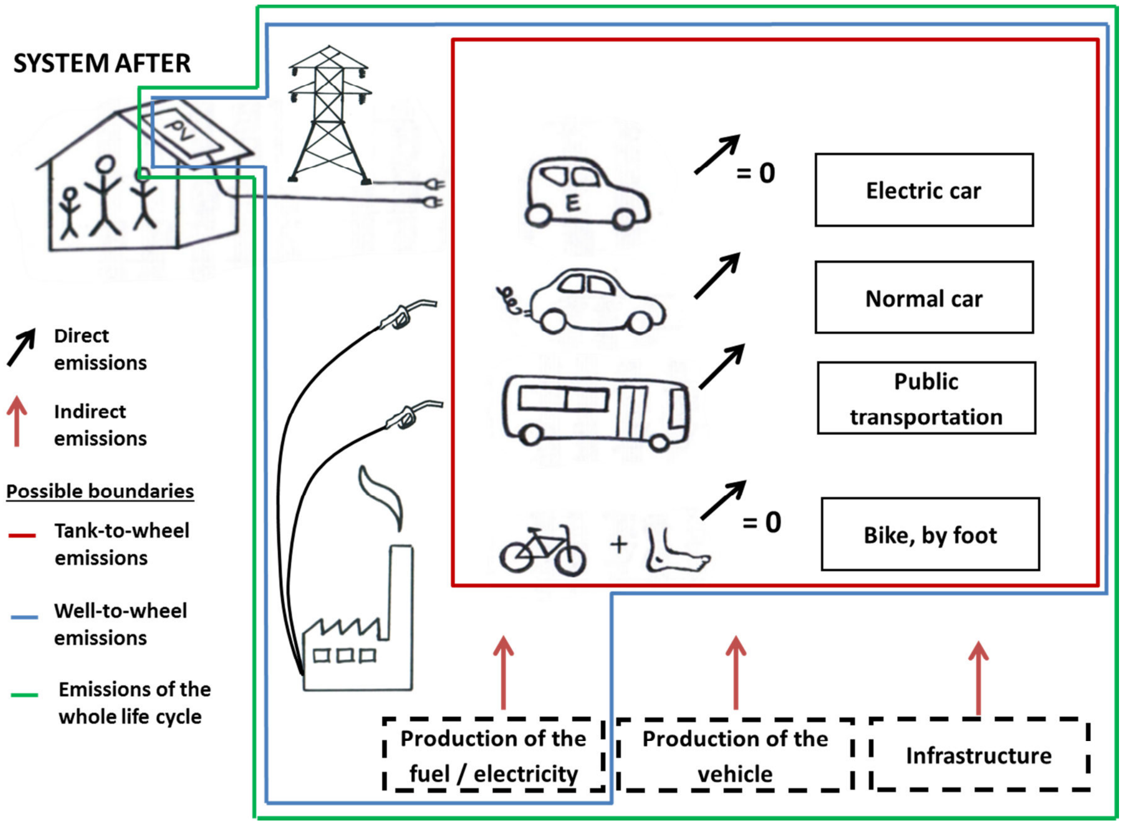


Figure 8: System boundaries for the CO2 emissions with the electric car

In the case study presented here, the mobility behavior of one household and the corresponding CO_2 emissions are going to be estimated. There are two characteristics of the system which make the situation special. First, the proband families will receive an electric car. Second, the electricity composition to run the electric car is dynamic over time of day and time of the year. Also the atmospheric conditions play a crucial role, since the PV energizing the electric car is dependent on the hours of sunshine per day.

With a tank-to-wheel approach the source of electricity will not impact the CO_2 emissions, since only the direct emissions will be taken into consideration. This would make the electric car a CO_2 neutral mode of transport, which, in reality, is only the case if the electricity comes from a CO_2 neutral source. Studies have shown that the environmental advantages of an electric car in direct emissions can be nullified by the life cycle emissions (ifeu - Institut für Energie- und Umweltforschung Heidelberg GmbH 2011). So if a sound comparison of the two systems should be carried out, the tank-to-wheel approach will not suffice.

So what is most appropriate, the well-to-wheel method or the LCA? A topic widely discussed when it comes to the estimation of environmental effects of an electric car is the production and the disposal of the battery. The results show that the impacts coming from this part of the car are not negligible (ifeu - Institut für Energie- und Umweltforschung Heidelberg GmbH 2011). This is a strong argument for applying a LCA. However, this method is particularly time consuming, depending on the level of chosen detail. Since in this case, the whole mobility behavior of one household will be assessed including several different transport modes, this method would be too extensive and exceed the time frame of this study. Furthermore the life cycle emissions are basically a constant additional emission factor that is not influenced by daily mobility choices. As the main aim of this study is not to give an absolute amount of CO_2 emissions per household, but rather to develop a tool that helps in identifying CO_2 emission saving potentials through changes in individual mobility behavior a LCA is not necessary. Thus, a well-to-wheel approach will be applied taking into account the direct emissions and the indirect emissions of the preliminary energy chain.

3.6. Geographical scope

As discussed above the exclusion of rail transport from the assessment narrows the possible application fields down to rural areas and small towns, whose public transportation system only consists of public busses. If the data is available, the model should not be limited to Bavaria but applicable to entire Germany to ensure a widespread use of the model. How state-specific parameters should be considered in the interpretation of the results will be discussed later on.

3.7. Temporal scope

The model should be used to estimate CO_2 emissions of present day mobility behavior, the analysis of past and future mobility scenarios is not the focal point here. To keep the model simple and the quantity of data to a minimum amount, the most recent data available will be used. To ensure the expressiveness of the results the data should not be older than 5 years.

3.8. Parameters considered for the tank-to-wheel emissions

As discussed in chapter 2.2.1 numerous parameters influence the direct emissions. The vehicle and engine characteristics should be collected as detailed as possible. This will be possible with the specific model/type of the vehicle.

As for data on the driving behavior, the collection might be a lot more difficult. To adapt the data collection effort to the available resources for each application, the level of detail of the driving behavior data should be variable.

Collecting detailed ambient condition data will be too time-consuming in most of the cases. Thus an assessment of this data should be avoided. Available average data should be used.

As mentioned in chapter 2.2.1 cold start emissions have a significant influence on the direct emissions and should thus be included. However, the assessment of ambient temperatures and parking times will be a huge effort which should be omitted by using average values.

Chapter 2.1 discussed that occupancy rates are essential to estimate the activity intensity and thus highly impact the CO_2 emissions on an individual level. To ensure a correct assessment, occupancy rates have to be considered. Two approaches could be used here, applying German average values or collecting the information on occupancy rates from the probands directly. The first one of the approaches would be easy to implement, however, leads to rather imprecise results. For an analysis on the micro scale level this impreciseness is undesired. So if possible, exact occupancy rates should be collected and applied.

For public transportation it will be more difficult to get exact occupancy rates from the probands, since an exact indication is either not possible or time-consuming. An average value for the corresponding occupancy rate should be used.

3.9. Summary of the system boundaries

Through clarifying the most important aspects of an emission assessment and adapting them to the sun2car project conditions, the large amount of factors that has to be considered was narrowed down to a manageable amount. The following estimation of a methodology to estimate CO_2 emissions will focus on the well-to-wheel emissions of one household. The considered transport modes are conventional and electric passenger cars, motorcycles and public busses. The geographical scope is limited to rural areas and small towns within Germany. Included in the assessment is the present daily life mobility behavior of individuals without holiday traffic. The data collection should be as detailed as possible where time issues allow it. In all other cases average values should be applied. Keeping these system boundaries in mind a research on existing emission models is carried out. From the available sources the best models to treat the research question presented here is to be selected.

4. Review on existing methods for CO_2 emission estimation and mobility data collection

The following chapter includes an extensive literature review on emission modelling approaches and corresponding emission models classified by tank-to-wheel and well-to-wheel models. Furthermore an overview of LCA databases is given which hold data that supplements the tank-to-wheel emission factors. Methods to collect mobility data are analysed and mobility surveys carried out in Germany are presented. Finally a concluding decision for the case presented here is made.

4.1. Emission modeling approaches and examples of existing models

To estimate emissions caused by transport, a number of emission models have been developed over the years. The following overview includes a detailed description of the models used in Europe and gives a short outlook on models applied elsewhere in the world.

Since road transport of all transport modes is the main contributor to most of the local pollutant and GHG emissions, research mainly focuses on emissions from road vehicles.

4.1.1. Emission modeling approaches

One way to generally classify emission models is a differentiation according to the generic type of modeling. A distinction is made between aggregated emission factor models, average speed models, traffic situation models and modal model.

The aggregated emission factor model operates at a simple level and uses a single emission factor for a particular type of vehicle that is operating at a general driving condition. Typically the driving conditions are divided into urban roads, rural roads and highways. This approach considers vehicle operations only on a rudimentary level, calculating mean values over given driving cycles. Due to the simplicity this type of model is mostly used on a large spatial scale for national or regional emission inventories.

Average speed models, as the name implies, use the average speed of each trip to estimate average emission rates for certain pollutants and specific vehicles. This way, however, different vehicle operation characteristics, such as acceleration patterns or gear change patterns, are not taken into account. Furthermore a detailed spatial resolution in emission predictions is not possible. Nevertheless this approach is widely used for regional and national inventories as well as, most recently, for local air pollution models. This is due to the fact that the handling of such average speed models is relatively easy and the required input data is generally available to the user.

These first two emission model types are mostly applied to medium- and large-scale scenarios. For emissions at a micro-scale level, on the other hand, modal models or traffic situation models are used.

To be able to include both driving cycle dynamics and speed into emission estimations, traffic situation models were developed. A specific set of driving cycle parameters defines the different traffic situation each correlated with average emission rates. The traffic situations are described qualitatively (e.g. the traffic is in “free-flow” or “stop and go”). This textual description is open to interpretation which might challenge the user and lead to inconsistencies. Traffic situation models can be used for regional and national inventories. They are, however, best suited to local applications as they deliver emission estimates for individual road links.

Modal models operate at the highest level of complexity allocating emission factors to the different modes of vehicle operation during one trip. They can be divided into “simple” modal models and instantaneous models. The “simple” modal model only takes a small number of different modes into consideration (e.g. idle, acceleration, deceleration and cruise). For each mode the emission rate is fixed for a defined vehicle and pollutant. The instantaneous model aims at delivering a more detailed description of the vehicle emission behavior. The emission rates are related to the vehicle operations during a series of short time steps (e.g. one second). Due to this level of detail the dynamics of the driving cycle are taken into account so that the emissions can be resolved spatially. A drawback of this model type is the high input data requirements. An exact and detailed measurement of the vehicle operation is required to make sure that the advantages of this model type are fully utilized. The collection of such information is cost-intensive and the use of the instantaneous model is thus restricted to the research community. (Abo-Qudais & Qdais 2005; Wang & Mcglinchy 2009; Boulter, McCrae & Barlow 2007)

This chapter was aiming at giving an overview of the existing emission modeling approaches. Following a review on existing emission models will be given. The above introduced terms for the different emission modeling approaches will be used. The classification of the models is done according to their system boundaries concerning the material flow concept. This way the focus is already set on determining the appropriate model for the case presented here.

4.1.2. Examples of tank-to-wheel emission models

The most commonly applied emission models in Europe are the COPERT 4 (COmputer Program to calculate Emissions from Road Traffic) and the HBEFA 3.1 (Handbook Emission Factors for Road Transport). Both models estimate the direct emissions from road transport.

4.1.2.1. COPERT

The COPERT 4 is a model developed by the CORINAIR Working Group on behalf of the European Commission (Esteves-Booth et al. 2002). Already used for emission inventories in the 1980s, COPERT’s fourth version COPERT 4 was launched in 2007. It is an average speed model and the emission factors are based on factors for hot exhaust emissions. The included variables are among others the vehicle fleet, vehicle age, driving patterns, fuel consumption and climate, thus showing a significant level of complexity. Furthermore factors for cold start and evaporative emissions are considered. This model operates at a medium and large scale. Due to its average-speed nature this model is not applicable for cases where changes in operational modes are faced (Abo-Qudais & Qdais 2005).

4.1.2.2. PHEM

A variety of European transportation emission models exist, however, comparisons between the results from different emission models have shown substantial differences. The need to develop a harmonized emission model was identified. In 2000 the European Commission 5th Framework project ARTEMIS (Assessment and Reliability of Transport Emissions Models and Inventory Systems) was established. Together with the COST's (European Cooperation in Science and Technology) Action 346, a model was developed that could simulate emission factors of any driving pattern and for different vehicle loads and gradients. This emission model called PHEM (Passenger Car and Heavy-duty Emission model) of the University of Graz calculates emissions and fuel consumption for every second of a user-specified driving pattern. This calculation is based on the engine power demand and the engine speed. Due to the high resolution of the result this model can be classified as an instantaneous model and is thus suitable for micro-level applications. (Wang & Mcglinchy 2009; Boulter, McCrae & Barlow 2007)

4.1.2.3. HBEFA

The HBEFA was first introduced in 1995, since 2010 version 3.1 is available. The model was originally developed by the Environmental Protection Agencies of Germany, Switzerland and Austria. By now Sweden, Norway, France as well as the JRC (European Research Center of the European Commission) are supporting HBEFA. The database holds emission factors for different traffic situations. These emission factors were retrieved from driving profiles on roads with defined traffic situations and calculated with PHEM. Each particular traffic situation is qualitatively defined by the level of service, the type of road, the speed limit and the area (urban or rural). This approach is equally applied to all vehicle categories including passenger cars, motorcycles, heavy duty vehicles, light duty vehicles, urban busses and coaches. Since the driving patterns and traffic situations are based on data from Germany, Austria and Switzerland, so far the use of the emission factors of this model is limited to the same area. (Wang & Mcglinchy 2009)

4.1.2.4. MEET, COST Action 319, TRENDS and NAEI

Apart from the above mentioned, further models have been developed but will only be discussed briefly.

Funded by the European Commission under the Transport RTD program, MEET (Methodologies for Estimating air pollutant Emissions from Transport) aims at providing a basic procedure for the whole of Europe to estimate the impact of all modes of transport on air pollution. Started in 1996 it was completed in 1998. The results were used, among others, for the above mentioned COPERT model. MEET was linked as well to the project COST Action 319 – "Estimation of pollutant emissions from transport" (TRL - Transport Research Laboratory 1999).

Another project funded by the European Commission was TRENDS (TRansport and ENvironment Database System). The aim of this project was the development of a tool able to calculated different environmental pressures due to transportation. The four principal modes of transport road, rail, air and water were considered. Apart from air pollutant emissions, waste generation and noise emissions from transport were also taken into account. The analysis of simple scenarios that included vehicle dynamics was provided. The geographical coverage included all EU15 members from 2003. (Aristotle University of Thessaloniki 2003)

The UK developed a national inventory system called NAEI (National Atmospheric Emissions Inventory) covering emissions to the atmosphere from sources such as power stations, household heating, agriculture, industrial processes as well as traffic. The latter are estimated using an average speed model which simulates the hot exhaust emissions and cold-start emissions of key pollutants as well as evaporative emissions of hydrocarbons from transportation. (Wang & Mcglinchy 2009; UK Department for Environment 2013)

4.1.3. Examples of well-to-wheel emission models

The above mentioned European models all focus on road transport and are only taking tank-to-wheel emissions into account. However, for numerous applications an all-mode approach is necessary. A further broadening of the system boundaries from tank-to-wheel to well-to-wheel assures that the emissions produced in the preliminary chain of the fuels are taken into consideration as well. The following models follow this more extensive approach.

4.1.3.1. TREMOD

Using the emission factors from HBEFA a model to estimate the pollutant emission for Germany from 1969 to 2030 called TREMOD (TRansport EMission MODel) was developed by the IFEU institute (Institut für Energie- und Umweltforschung Heidelberg GmbH). It takes direct CO_2 emissions and preliminary links of the energy chain into account. Apart from road transport rail, inland water and aircraft transport modes are also considered. Due to its complexity and its extent the calculation tool TREMOD is not publicly available. TREMOD is widely used for Life Cycle Analysis and environmental comparisons like ProBas, Renewbility, GEMIS, Umberto, UmweltMobilCheck, EcoPassenger and EcoTransIT. (ifeu - Institut für Energie- und Umweltforschung Heidelberg GmbH 2013)

4.1.3.2. TREMOVE

Based on the COPERT data, the model TREMOVE was established by Transport & Mobility Leuven in a service contract for the European Commission, Environment Directorate-General. In a well-to-wheel assessment it models all land and maritime transport emissions. Furthermore it estimates the transport demand, the modal split and the vehicle stock turnover covering the years from 1995 to 2030. As a policy assessment model it is able to estimate the effects of different policies for transportation and environmental issues on transport emissions. Currently the model is being fed with data from 31 different countries ensuring a Europe wide coverage. (Transport & Mobility Leuven 2007) The model itself is publicly available on the TREMOVE website (Transport & Mobility Leuven 2012).

4.1.3.3. MOBILE6/MOVES

The most extensive and widely used model outside Europe is the US Environmental Protection Agency's MOBILE 6 which has been replaced recently by the new modeling system MOVES (Motor Vehicle Emission Simulator). The instantaneous modeling approach is based on energy demand. In addition to the "tank-to-wheel" energy and exhaust emission processes MOVES also includes “well-to-tank” emissions. Considered modes are highway vehicles such as cars, trucks and motorcycles covering a broad range of pollutants. Apart from the conventional fuels (diesel and gasoline) the model covers Compressed Natural Gas (CNG), E85 (ethanol gasoline mix), M85 (methanol gasoline mix), Liquefied Petroleum Gas (LPG) and electricity. MOVES consists of a database for emission factors and transport activity data and a tool for emission inventories and scenario calculations (up to the year 2050) at multiple scales (from individual links to national scales) (Deutsche Gesellschaft für Internationale Zusammenarbeit 2012). The program is publicly available as a free download on the US EPA’s web page. (United States Environmental Protection Agency 2013)

4.1.4. Choosing the appropriate CO_2 emission model

The discussed models have different characteristics and different areas of application. To figure out which one is most applicable to the here presented case study an investigation of advantages and disadvantages of the most important models will be carried out. Important points are:

- geographical coverage
- scale of application (micro, macro-scale)
- considered modes of transport
- type of approach (well-to-wheel, tank-to-wheel)
- availability, costs

Table 1 shows the five most commonly used models in Europe and the US model MOVES together with their key characteristics. The plus and minus sign illustrate which of these factors speaks for or runs a counter application of the model in the intended scope presented here.

Table 1: Comparison of transport emission models and databases adapted from (Deutsche Gesellschaft für Internationale Zusammenarbeit 2012)

	HBEFA		TREMOD		COPERT		TREMOVE		PHEM		MOVES	
Developed by	INFRAS AG		ifeu Heidelberg		EMISIA		TML, KU Leuven		University of Graz		US Environ-mental Protection Agency	
Commissioner	Several federal environ-mental authorities in Europe		Federal Environ-mental Agency of Germany (UBA)		European Environ-ment Agency (EEA)		European Commission DG Environment		European Cooperation in Science and Technology (COST)		US Environ-mental Protection Agency	
Transport Modes	Road	-	Road, Rail, Inland Water and Aircraft	+	Road	-	Road, Rail, Inland Water, Maritime	+	Road	-	Road (highway modes)	-
Modeling approach	Traffic situation model	+	Traffic situation model	+	Average speed model	-	Average speed model	-	Instantaneous model	+	Instantaneous model	+
Resolution	Tank to wheel	-	Well to wheel	+	Tank to wheel	-	Well to wheel	+	Tank to wheel	-	Well to wheel	+
Software requirements	MS ACCESS	+	MS ACCESS	+	MS ACCESS	+	MS ACCESS and EXCEL, WINZIP, GAMS	-	No requirements	+	MySQL, Java	+
Software availability	order by registra-tion, fee 250 €	-	not publicly available, only for coopera-tion partners	-	order by registration, fee for country data, 300 € each	-	free download	+	ARTEMIS/COST 346: Input data 4000 €. Non ARTEMIS/COST 346: Input data 6000€	-	Free download	+
Data availability	Europe - individual purposes	+	Germany - national level	-	Europe - national level	-	Europe - national level	-	Europe - individual purposes	+	US - national and regional level	-
Typical application	Micro to Macro Scale	+	Macro Scale	-	Macro Scale	-	Macro Scale	-	Micro Scale	+	Micro to Macro Scale	+

All of the above mentioned models cover CO_2 emissions, as it is the most important GHG emitted by transportation.

The results from the table above show that COPERT is the least suitable model for the purpose of this project. First it covers only tank-to-wheel emissions, is only applicable for a macro scale and additionally has a fee for each country data set. Being an average speed model, would only allow a very simple estimation which is insufficient for the intended purpose. The well-to-wheel model TREMOVE which developed out of COPERT would cover more points essential for the application presented here, is downloadable for free and covers road, rail, inland water and maritime and estimating well-to-wheel emissions. However, it is still an average speed model and designed for the national level which makes its use for individual purposes impossible.

The PHEM model on the other hand is suitable for micro-scale applications due to the instantaneous calculation of emissions. The drawback here is the data input requirements that are high considering the user has to input complete driving cycle data. Also the well-to-tank emissions are not considered, which does not match the defined system boundaries. Furthermore the license is very costly, making the model limited to a small research community.

The MOVES model does cover a number of points necessary for the application intended here, such as well-to-wheel emissions and being freely available. However, it is limited to highway transport modes. The model being developed for the US works in its disadvantage as well.

A model which has been developed for the macro as well as for the micro scale is HBEFA. The downsides of this model are that only tank-to-wheel emissions are taken into account as well as that the model is only covering road transport. An important plus is that the model works with a traffic situation approach which guarantees a good level of detail.

A model even closer to what is searched, is the TREMOD model of the German Federal Environmental Agency. Not only does it cover all modes of transport, but also well-to-wheel emissions. Since part of the model is based on HBEFA it also applies a traffic situation approach. As shown with applications as UmweltMobilCheck or EcoPassenger it is suitable for individual scale scenarios as well. Even though the TREMOD model is the best one for the here intended application, it cannot be applied to this project, since it is not publicly available. A request to use the model at the German Environment Agency (UBA) was denied; however, average CO_2 emission values calculated with TREMOD are available from the Mobilität in Deutschland (MiD) survey. These values will be used for a validation of the result.

Apart from MOVES none of the models above cover electric vehicles. This and the fact that only TREMOD would cover the needs of the here presented application but is not available leads to the conclusion that a new model has to be designed.

As a basis the tank-to-wheel emission factors from HBEFA will be used, since the traffic situation approach is best suitable for the application presented here. Furthermore it is an established and widely used database, which makes the data reliable. This emission data then has to be complemented with well-to-tank emission factors. How to retrieve those will be discussed in the following chapter.

4.2. LCA databases

Due to LCA being more and more widely applied, the sources for data on the emissions from fuel and electricity production are numerous. Three of the most commonly used LCA databases will be shortly discussed below. All of them give back emissions for a range of air pollutants and greenhouse gas emissions, all covering CO_2.

4.2.1. Ecoinvent

Ecoinvent is the LCA database of the Swiss Centre for Life Cycle Inventories. This competence centre is a collaboration of the Swiss Federal Institute of Technology Zurich (ETH Zurich) and Lausanne (EPF Lausanne), the Paul Scherrer Institute (PSI), the Swiss Federal Laboratories for Materials Testing and Research (Empa), and the Swiss Federal Research Station Agroscope Reckenholz-Tänikon (ART). With experience of more than 20 years the ecoinvent database is worldwide the most extensive database for LCA data. It currently holds several thousands of LCI (Life Cycle Inventory) datasets covering the areas of agriculture, energy supply, transport, biofuels and biomaterials, bulk and speciality chemicals, construction materials, packaging materials, basic and precious metals, metals processing, information and communications technology, electronics and waste treatment. The database can be implemented into LCA software such as openLCA (open source) or GABI (with costs). For educational users the licence is 2500€. (Swiss Centre for Life Cycle Inventories)

4.2.2. GEMIS

GEMIS (Globales-Emissions-Modell integrierter Systeme) is a database and life-cycle and material flow analysis model developed by the IINAS (International Institute for Sustainability Analysis and Strategy). GEMIS is used in around 30 countries for environmental, cost and employment analyses. The covered areas are energy sources, heat and electricity, materials and transport systems. The model takes into account all processes from resource extraction to final energy or material use. Database and model are freely available at download at the IINAS homepage. (International Institute for Sustainability Analysis and Strategy 2013)

4.2.3. ProBas

The UBA together with the Institute for Applied Ecology developed the web-based LCA database ProBas (Prozessorientierte Basisdaten für Umweltmanagement-Instrumente). ProBas is a library of life cycle data, bringing together data from several publicly available databases, among others, the above mentioned GEMIS database. The aim is to provide the interested public access to basic data for environmental management. All together there are over 8000 datasets available covering subjects such as energy, materials and products, transport, waste treatment and other services. (Umweltbundesamt)

4.2.4. Comparison of the different LCA databases

As shown, several sources for well-to-tank emission factors are available. The following paragraph will discuss which source for the well-to-tank emissions will be used.

Having a closer look at the data available in ProBas it becomes clear that the data available for fuels in ProBas is mainly based on GEMIS data. To check how different the values from different sources are, values for diesel from both ProBas and ecoinvent[1] were compared.

Table 2: Comparison of Life Cycle values for diesel from different databases

Source	Value original	Recalculated Value	Name of the process	Reference year	Reference area
ecoinvent	0.52 kg CO_2-Eq /kg of fuel	0.432 kg CO_2-Eq/L of fuel	(Diesel, low sulphur, at regional storage, RER)	2005	RER (geographical code for Europe)
ProBas (based on GEMIS)	12538 kg CO_2-Eq/TJ	0.446 kg CO_2-Eq/L of fuel	(DieselMix - DE (inkl. Biokraftstoffe))	2010	Germany

To be able to compare both results the units had to be adapted. Ecoinvent only gives back CO_2 equivalents as a result, which means that the result is the sum of all greenhouse gas emissions as CO_2 equivalents. To match the unit, the according value was retrieved from ProBas. As the unit to compare both values, “kg CO_2-Eq/L of fuel” was chosen. To recalculate the values a density of 0.8 kg/L and a heating value of 9.9 kWh/L were applied (Deutscher Wasserstoff- und Brennstoffzellen-Verband e.V.). Due to the fact that the ecoinvent value is an average value for Europe and the ProBas value is valid for Germany a direct comparison cannot be done. However, seeing that both values from two different databases lie that close together assures that the values are reliable. For the well-to-tank emission estimation of the model developed here, the ProBas database will be used, since the geographical scope of the data is narrowed down to Germany.

4.3. Mobility surveys

In Germany mobility surveys have a long tradition and extensive knowledge does exist when it comes to mobility data collection. In the following the main approaches to collect mobility and additional household data are presented along with examples of mobility surveys carried out in Germany.

4.3.1. Methods to collect mobility data

In a mobility survey the transport activity information of a sample of probands is collected. The mobility data includes the number of trips per period considered, the trip length (in vehicle kilometers) and the occupancy rate. Furthermore the mode of transport should be specified. Whether additional information such as the road gradient, the traffic situation or ambient conditions is collected depends on the used method. There are two main approaches to get the mobility data, either the probands have to document their mobility patterns manually or the movements are tracked automatically via GPS (Global Positioning System).

[1] licence was available from a research project of the author completed at the Technical University of Denmark

4.3.1.1. Travel diaries

Most commonly used, until now, are surveys that ask the respondents to document their trips manually via a travel diary. The travel diary consists of questions about all trips of a certain period including information on the mode of transport, the trip length, the trip duration and the trip purpose. Depending on the desired outcome, the number of fellow passengers might also be asked. How such a travel diary can look like is shown below (Figure 9).

2006 Flagstaff Travel Diary

Please record all of your trips, whether you are a passenger, driver, or pedestrian.
The information on the first row is included only as an example. Please refer to the instructions if you are not sure how to record your trip.

Name: **Address:** **City/State/Zip:** **DIARY DATE:**	**STARTING POINT ADDRESS** **Street Address:** **City/State/Zip:** **Nearest Cross Streets:** &	**I did not leave the house today:** ❑ **If using motor vehicle, list odometer reading:** at beginning of day: at end of day:

trip #	DESTINATION (address, building or nearest cross streets)	trip start time hour:min	am/pm	trip arrival time hour:min	am/pm	trip purpose	travel method	est. trip miles	number of people in vehicle (inc. yourself) children	adults
example	Puente de Hozho Elementary School Fourth & Linda Vista	7:13	AM	7:22	AM	1. go home 2. personal business 3. shopping 4. school 5. work commute 6. other work/business 7. social/recreation 8. eat a meal 9. drive passenger 10.change travel mode 11. other:	1. car or light truck (driver) 2. car or light truck (passenger) 3. bus/transit: route(s): ❑ 66 ❑ 2 ❑ 3 ❑ 4 ❑ 5 4. school bus 5. large commercial truck 6. motorcycle 7. taxi (passenger) 8. bicycle 9. walk 10. other:	2 miles	1	1
1	&	:		:		1. go home 2. personal business 3. shopping 4. school 5. work commute 6. other work/business 7. social/recreation 8. eat a meal 9. drive passenger 10.change travel mode 11. other:	1. car or light truck (driver) 2. car or light truck (passenger) 3. bus/transit: route(s): ❑ 66 ❑ 2 ❑ 3 ❑ 4 ❑ 5 4. school bus 5. large commercial truck 6. motorcycle 7. taxi (passenger) 8. bicycle 9. walk 10. other:			
2	&	:		:		1. go home 2. personal business 3. shopping 4. school 5. work commute 6. other work/business 7. social/recreation 8. eat a meal 9. drive passenger 10.change travel mode 11. other:	1. car or light truck (driver) 2. car or light truck (passenger) 3. bus/transit: route(s): ❑ 66 ❑ 2 ❑ 3 ❑ 4 ❑ 5 4. school bus 5. large commercial truck 6. motorcycle 7. taxi (passenger) 8. bicycle 9. walk 10. other:			
3	&	:		:		1. go home 2. personal business 3. shopping 4. school 5. work commute 6. other work/business 7. social/recreation 8. eat a meal 9. drive passenger 10.change travel mode 11. other:	1. car or light truck (driver) 2. car or light truck (passenger) 3. bus/transit: route(s): ❑ 66 ❑ 2 ❑ 3 ❑ 4 ❑ 5 4. school bus 5. large commercial truck 6. motorcycle 7. taxi (passenger) 8. bicycle 9. walk 10. other:			

Figure 9: Travel diary (Flagstaff Metropolitan Planning Organization 2007)

This method has the big advantage that it collects not only quantitative but also qualitative data, such as information on trip purposes and transport modes. Furthermore it is a method that can be carried out without any expensive technology. However, besides its simplicity the method also has some drawbacks.

To ensure the correctness, the trip length should be supported with GIS (Geographic information systems) information as the estimation of distances by the probands can often be imprecise. A common problem is furthermore the under-coverage of trips. The information of the probands is often incomplete, especially when it comes to short trips. Given the large amount of information that is requested for one trip, the effort to fill in the travel diary is considerable. Due to this the travel diary method is limited to short time periods. More than one week of data acquisition will not be possible. (Österreichisches Bundesministerium für Verkehr 2011)

As for the analysis of the data it makes a difference if the travel diary is done in paper form or online. While the paper version has the advantage that the probands have them on hand at all times and can fill them out instantly, the automated entry of an online version saves substantial post-processing efforts.

This method has been used in Germany a number of times. Nationwide surveys applied the travel diary but also surveys at a smaller scale as well, e.g. in the cities of Hannover, Steinfurt and Heinsberg (infas Institut für angewandte Sozialwissenschaft GmbH 2013), (Planersocietät-Stadtplanung 2011), (Planersocietät-Stadtplanung 2012).

Most widely known is the survey MiD, formerly known as KONTIV (Kontinuierliche Erhebung zum Verkehrsverhalten). In this nationwide survey 50,000 households are questioned about their mobility behavior on one specific date. The survey is being conducted every couple of years, the last one being done in 2008 and the next one planned for 2015 (Bundesministerium für Verkehr 2013a).

While MiD covers only the trips of one day, the Deutsche Mobilitätspanel (MOP) is focused on the mobility behavior of one week in three consecutive years of the same representative group of people. In the last survey around 1,000 households have documented their trips (Bundesministerium für Verkehr 2013b).

4.3.1.2. GPS

As shown above, the travel diary has some drawbacks especially concerning the completeness and accuracy of the data. With the progress of technology another way of tracking has become more and more used: GPS. Smartphones with integrated GPS systems being on the rise, this method even becomes suitable for mass use.

First trials using GPS for travel data collection where carried out in the 1990s. Originally the idea was only to supplement travel diary information with correct trip lengths and trip durations. Wolf et al. 2001 give an overview of the beginnings of this technology used for mobility research purposes.

At present the efforts go even further aiming at complete substitution of the travel diaries. The current state of research on this topic is shown below.

Some of the trip data elements can be easily assessed with the GPS information. Trip length can be calculated from the GPS positions during the trip as well as the trip durations (beginning and end of the GPS movement). Trip origin and trip destination addresses can furthermore be estimated through GPS latitude and longitude. One problem here is the data gaps that arise from the fact that GPS tracking fails when the device is without a signal, which can be the case in tunnels or mountain valleys. Assuming the technology is working properly this information is a lot more precise than it could have been collected through a travel diary. However the collection of some other parameters is not that simple.

The trip purpose is an important element to map a complete mobility pattern. In combination with GIS data on the land-use of the trip destination and the dwell time, the trip purpose can be identified in a lot of cases. Wolf et al. 2001 describe in detail the methodology of this approach.

For example when the address of the work place or school is known then the assignment is easy and often accurate. Still, for other trip purposes this is less explicit. In densely built-up areas GPS tracking is often not precise enough to identify the address the proband wants to arrive at. Also sometimes the trip destination does not allow an unambiguous assignment of the trip purpose. A shopping mall for example could lead to the conclusions that the test person is shopping for daily goods, is meeting friends or visiting the movies. (Wolf, Guensler & Bachman 2001; Österreichisches Bundesministerium für Verkehr 2011)

A further crucial part of the travel data is the mode of transport used. The Institute of Automotive Technology at the Technical University of Munich is currently developing a smartphone tool to track traveling operations and to automatically assign the right mode of transport. This is done through analyzing the speeds, the acceleration patterns and a cross reference of the trip data with GIS data on the way (detection of subway or bus stations). This technology has already been tested within the eFlott project, a fleet test with electric vehicles in the model region Munich (Technische Universität München), and is currently being used and further developed in the course of the sun2car project. While the assignment works well for some of the modes, the identification of underground transport is especially error-prone due to the intermitted GPS signal.

The number of passengers in a private car can be determined if all members are equipped with a GPS tracking device. Identical driving patterns lead then to the conclusion that the members are travelling together. If, however, not all members are equipped with a GPS device the assessment of the number of passengers will be distorted. Is the proband travelling with public transportation, the information on the occupancy rate has to be either collected from the probands or average occupancy rates have to be applied.

All these points have also been analyzed by the University of Natural Resources and Life Sciences in Vienna within the project MobiFIT (Mobilitätserhebung basierend auf Intelligenten Technologien). The main objective was to retrieve mobility data that can be compared to the results of survey-based mobility studies (Universität für Bodenkultur Wien). Here as well the collection of qualitative data is still erroneous. Summarized results of the findings so far can be found in the KOMOD (Konzeptstudie Mobilitätsdaten Österreichs) report. (Österreichisches Bundesministerium für Verkehr 2011)

From the results of current research it becomes clear that the technology is not yet technically mature enough to deliver all needed information without an additional manual follow-up survey. A further drawback is the fact that the necessary software is not publicly available and that all probands have to be equipped with smartphones which will lead to high costs. However, research is being pushed to solve data analysis problems and the wide spread use of smartphones with the option of GPS tracking might soon solve the issue of expensive technology.

As soon as the method becomes more accurate in assigning the right mobility information it will replace the travel diary as it has great advantages. Apart from the mentioned higher accuracy and completeness of the data, it also reduces the respondent's burden of filling out a diary every day. Even though a telephone or face-to-face interview to brief the probands cannot be avoided, no extensive follow ups are necessary. The restriction of the travel diary to a limited number of days can be extended to multi-week or even multi-year periods, which holds huge potential for in depth mobility analyses.

4.3.2. Methods to collect vehicle and household data

Apart from the mobility data which can be tracked with either travel diaries or GPS some additional data is needed. Detailed information on the vehicles used is crucial for a correct CO_2 emission assessment. The information on the private vehicles has to be collected directly from the probands. Information on public transportation must be retrieved from the local transport companies.

Basis of every data collection of mobility behavior is furthermore the collection of general information on the probands, which include the age, the gender, the current occupation and the income level. This data is necessary to be able to analyze statistical relations between the different results. Variations across the sample can be explained and the variables that have the biggest influence on the outcome can be identified.

To collect this data different methods can be applied which are be discussed below.

4.3.2.1. Written survey

A common method to carry out surveys is a questionnaire in written form. Depending on the type of distribution they can be further divided into paper surveys and online surveys. Both survey types have the advantage that the respondent is not under time pressure. Furthermore the interviewer effect does not occur, thus the answers of the probands are not biased by the behavior of the interviewer.

Sending out paper surveys by mail is a conservative way of reaching out. The above mentioned advantages, however, go hand in hand with the disadvantages of a low return rate and the possibility that questionnaires can be sent back incomplete or filled out incorrectly. The printing and mailing process and the fact that the answers have to be evaluated manually afterwards furthermore result in considerably high costs and time efforts.

To lower these costs a survey can also be conducted through an online form. This saves money and has a better return rate. Furthermore it can be easily distributed and the answers are retrieved immediately after filling out the form. Further advantages are the automated collection of the data and the possibility of checking the plausibility of the answers directly at input. (Statistische Ämter des Bundes und der Länder 2011)

One problem of this method is that certain social groups could be overwhelmed by the technology (e.g. elderly people) and thus be underrepresented.

Both paper and online surveys present a risk that the proband does not understand the instructions properly and will thus fill out the form incorrectly. If either one of the two possibilities is conducted, it should be complemented by a telephone hotline where the test person can get assistance with filling out the form.

4.3.2.2. Interviews

Interviews are another way of collecting data. The contact to the probands is direct and the interviewees have the possibility of communicating with the interviewer. The interview is either done by telephone or face-to-face.

Both methods have the advantage that questions of the interviewee can be answered right away which guarantees a high data quality. The direct contact also helps to motivate the probands to participate in the survey which results in high return rates. The disadvantages of these methods are the already mentioned interviewer effect and the fact that both methods are time and money consuming. To ensure unbiased answers the interviewers have to be specially trained.

With telephone interviews the costs can be lowered, this advantage, however, can be outweighed by the following weaknesses. Due to the technology the interview time has to be kept short. This and the fact that a graphical presentation of the issue is not possible, makes the telephone interview not suitable to collect data on complex topics.

If the questions are too complicated a face-to-face interview is needed. The interviewee has more time at his/her disposal and an ideal understanding of the questions can be achieved with additional explanations or supporting illustrations. Due to the large amount of time necessary for the interviews and the travelling this method is very costly. (Statistische Ämter des Bundes und der Länder 2011)

4.3.3. Conclusions for the survey design

As shown above, the variety of different methods is large. Within this thesis a survey should be designed which presents the most efficient combination of the existing tools to collect mobility data and is expected to deliver the most satisfying results.

Given the current state of the technology GPS tracking it is not the method of choice. Even though it has a large potential to deliver accurate mobility behavior data, the occurring errors, the availability, the need for a follow-up survey and the costs speak against it. Thus the following efforts will be focused in designing a travel diary. To ensure accurate results, the answers should be further supported with GIS data.

The most suitable way to collect the general data on the households is considered to be the online survey. This is due to its cost- and time-effectiveness and easy distribution. Furthermore the analysis of the results can be done in only one step without the need of manually entering the data in a database. As the subject of the questions is rather simple this method choice can be justified. To give the interviewees the possibility to ask questions a hotline should be available during the time of the survey.

4.4. Summary of the literature review

The literature review presented gave an overview of existing models and methods to carry out a comprehensive CO_2 emission estimation. From the existing emission models the TREMOD model was identified as the most suitable one. Due to a missing inclusion of the electric car and the fact that the model is not available to the public, the need to develop a new model was identified. For the basic tank-to-wheel emission factors HBEFA was chosen. These values have to be supplemented by well-to-tank emission factors. From the three presented LCA databases, ProBas was chosen to be the database of choice. As for the mobility data collection method, two possibilities were identified, the travel diary and GPS tracking. Due to the current state of research the GPS method still shows some shortcomings. Thus the travel diary was chosen to be the best suitable data collection method together with an online survey collecting household and vehicle data.

5. Development of the model and the mobility survey documents

The development of the methodology consists of three steps, the setup of a database, the programming of the CO_2 emission model and the design of the survey documents to collect the necessary input data.

5.1. Database setup

Since the need to construct a new model was identified, the best way to use the available resources and to integrate them into one model has to be worked out. The following chapter gives an insight to the design process and answers to the main questions that may arise while developing the model.

5.1.1. Basic structure of the model

In chapter 3 the system boundaries were determined. In order to be able to properly compare different modes of transport, such as conventional and electric vehicles, a well-to-wheel approach has to be applied. The well-to-wheel emissions are divided into the emissions of the preliminary energy chain (well-to-tank emissions) and the direct emissions occurring during the combustion process (tank-to-wheel emissions).

The next question to be clarified is which output is desired. Since the model is being developed in order to do a household based inventory the reference unit should be the transport-related CO_2 emissions per household, broken down into the transport-related CO_2 emissions per family member.

The input data will be all parameters that describe transport processes such as information on the vehicle used, travel data (distances, speeds etc.) and the occupancy rate, which is essential to calculate individual-related CO_2 emissions. The figure below (Figure 10) depicts the basic structure of the model.

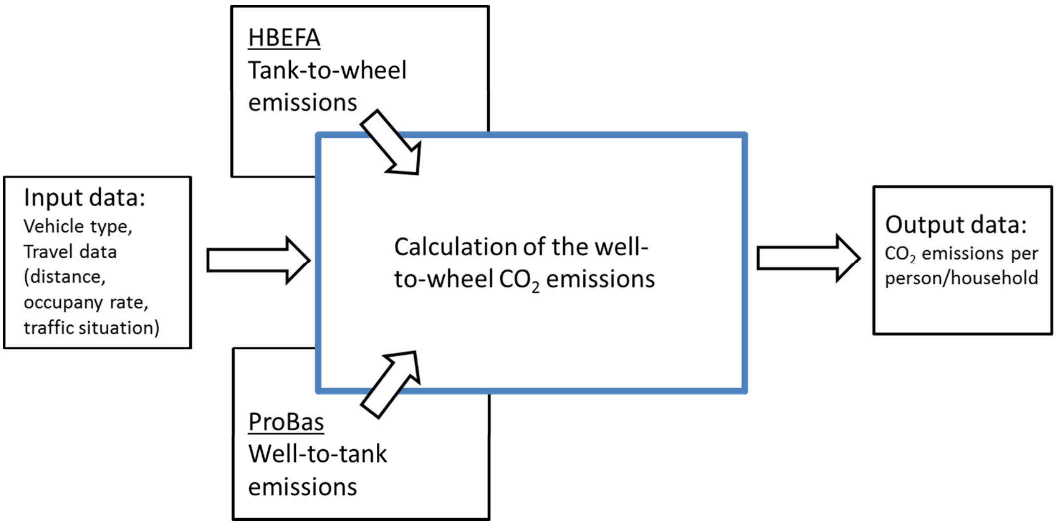


Figure 10: Basic structure of the model

The trip-specific input data will vary from case to case and has to be collected anew for each one of them. How this can be done was discussed in chapter 4.3.

Then the sources for the emission factors HBEFA and ProBas were chosen. How the required data is retrieved from these databases is discussed in the following paragraphs.

5.1.2. Tank-to-wheel emission and consumption factors

The tank-to-wheel emission factors are obtained from HBEFA, a Microsoft Access based database. The following chapter will explain in detail how HBEFA is structured and how the necessary data is retrieved.

5.1.2.1. Description of HBEFA

Chapter 4.1.2.3 already gave a short overview of the basic principles of HBEFA. Following the structure and information held by this database is being reviewed in detail to evaluate how the data can be implemented into the model.

The most obvious possibility to use the HBEFA data would have been to connect the developed model directly with the HBEFA database. This approach, however, was dismissed due to the following reasons. The first reason was the availability. With the use of HBEFA being restricted to paying users also the model developed here would have been limited to users owning a license. Even though HBEFA is widely used, holding a license cannot be taken for granted. A restriction though could not be accepted since it would have excluded potential target users such as small municipalities or individual households. Another point was the fact that the database of HBEFA is very extensive, holding a lot more information than necessary for the case applied here. Using the whole database would mean a very complex structure of the model that could confuse the user and would lead to longer computing times. Finally the programming of the interface would have been quite complex which, given to the above mentioned reasons, would not be necessary.

Accordingly the approach was to reduce the data held by the HBEFA database down to the most essential information, ensuring the simplest design and the most user-friendly operability.

In the following, the structure of HBEFA will be presented step by step and it will be discussed which part of the data is used for the model. The entry mask of HBEFA will serve as guidance for the procedure and is shown below (Figure 11).

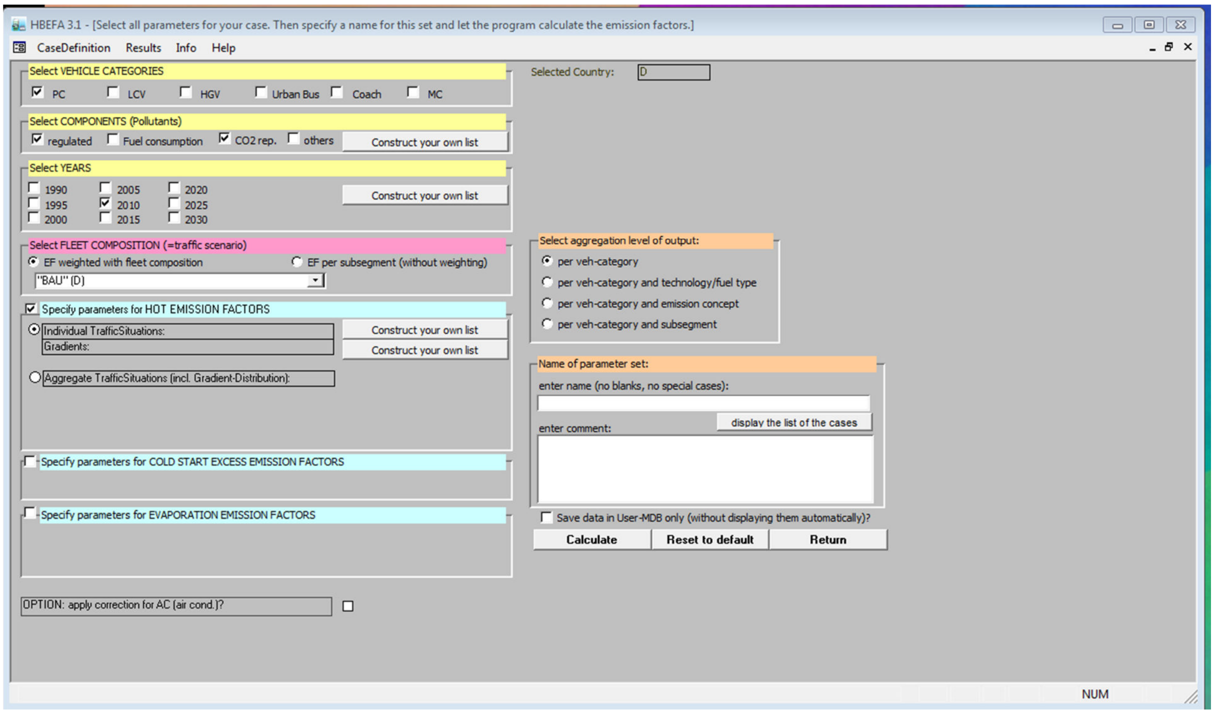


Figure 11: Entry mask in HBEFA

In a first step the vehicle categories can be chosen. From the six different categories only the passenger cars, motor bikes and the urban bus are of importance for the model. Utility vehicles will be excluded, since the focus lies on individual private transport. The long distance bus will commonly be used for holiday traffic and does also not lie within the scope of the study.

The database also covers a number of other pollutants (Annex 1 gives an overview) from transportation. Setting the focus on CO_2 emissions, all data sets covering pollutants other than this can be omitted.

The HBEFA database holds data from the year 1990 up until future scenarios in 2030. As the new model is supposed to calculate present CO_2 emissions, data covering the past is not of importance as is future data. Thus the reference year 2010 is chosen. Not only is it close to the present year (2013) but 2010 is also the year for which emission factors per vehicle subsegment are available. This information is necessary in order to distinguish between different vehicles. The option “emission factors per fleet mix” would not make an analysis on an individual basis possible. The vehicle segments hold data on vehicles with the same fuel type and size. The different fuel types covered are: gasoline, diesel, natural gas/gasoline mix, liquid gas and E85. From a conversation with Infras who developed HBEFA the information was obtained that the HBEFA values for the natural gas/gasoline mix, the natural gas for passenger cars and the liquid gas are not very reliable due to the small amount of empirical data. Still they were kept in this model but treated with caution. The size differentiation for passenger cars and motor cycles is done according to their cubic capacity, urban busses are divided into classes according to their tonnage. A further classification into emission concept subsegments is done. For the newer cars it is described by the Euro class, for older ones with ECE classification or the year of construction. The number of different subsegments for the passenger cars is 96, for the motor cycles46 and for the urban bus 77. A list of the available vehicle subsegments in HBEFA is provided in Annex 2.

As already mentioned HBEFA is a model applying a traffic situation approach. The traffic situations are defined by four parameters: the area, the road type, the speed limit and the level of service. The area makes a distinction between rural and urban. For each area different road types exist, eight different ones in the rural area, seven in the urban area. The different road types are given in Table 3. The highlighted cells show which combinations of road type and speed limits are possible. These 69 combinations are furthermore combined with 4 levels of service (freeflow, heavy, saturated/congested, stop+go) leading to 276 different traffic situations. For each traffic situation and each vehicle type, an emission factor is stored in the database with the unit grams of CO_2 per vehicle kilometre. One further option is to choose the road gradient in a range from 0% up to ±6%.

Table 3: Traffic situations in HBEFA

			Speed Limit [km/h]											
Area	Road type	Levels of service	30	40	50	60	70	80	90	100	110	120	130	>130
Rural	Motorway-Nat.	4 levels of service												
	Semi-Motorway	4 levels of service												
	TrunkRoad/Primary-Nat.	4 levels of service												
	Distributor/Secondary	4 levels of service												
	Distributor/Secondary(sinuous)	4 levels of service												
	Local/Collector	4 levels of service												
	Local/Collector(sinuous)	4 levels of service												
	Access-residential	4 levels of service												
Urban	Motorway-Nat.	4 levels of service												
	Motorway-City	4 levels of service												
	TrunkRoad/Primary-Nat.	4 levels of service												
	TrunkRoad/Primary-City	4 levels of service												
	Distributor/Secondary	4 levels of service												
	Local/Collector	4 levels of service												
	Access-residential	4 levels of service												

This highly detailed information leads to an extensive amount of data. In HBEFA, however, there is the possibility to get back emission factors specific for each subsegment but aggregated over the traffic situations. Two levels of aggregation are for selection. The first is an aggregation of all traffic situations and road gradients for three different road types (urban, rural and highway). On the highest aggregation level, all traffic situations are aggregated, leaving one emission factor per subsegment.

For the model being developed within this thesis, a micro scale application is intended. Depending on the application the model is used for, a detailed approach to the traffic situations might be desired. To leave this decision to the user it was decided to develop a model for all three levels of detail. The most detailed level will hold all traffic situations and four different options of road gradients (0%, ±2%, ±4%, ±6%). The other two levels of detail use aggregated traffic situations and a German average for the road gradient.

A further option in HBEFA is to choose whether or not to include cold start emissions. This topic was elaborated on in chapter 2.2.1, leading to the conclusion that cold start emissions should be considered. HBEFA holds this information only for passenger cars and light duty vehicles, which are irrelevant for this case. Cold start emissions vary according to the ambient temperature, the parking time and the trip length. In HBEFA various combinations for the conditions are available. As collecting the required information for the cold start emissions will mean substantial additional effort in the data collection, a German average for the parking time and trip length pattern is chosen. The temperatures are aggregated over the whole year. This way the data is narrowed down to one data set holding one cold start emission factor for every passenger car subsegment. The unit of the emission factor is grams of CO_2 per start.

Evaporation emissions are only relevant for the emission of hydrocarbons thus this parameter is not of relevance for the CO_2 emissions and will not be further considered.

The last parameter to choose in HBEFA is whether the car has air conditioning or not. Since it might be interesting to analyse this parameter with the model, both options are kept. This option again only exists for passenger cars and not for the urban bus.

5.1.2.2. Chosen tank-to-wheel emission factors

With the total data stored in HBEFA reduced to only the data important for the development of the model, the five following datasets are left. The German expression will be used to name the data files as the users are expected to speak German and are here stated in italic.

- Emission factors for passenger cars without air conditioning (*Pkw_ohne_Klimaanlage*)
- Emission factors for passenger cars with air conditioning (*Pkw_mit_Klimaanlage*)
- Emission factors for urban busses (*Linienbus*)
- Emission factors for motorcycles (*Motorrad)*
- Cold start emission factors for passenger cars (*Kaltstart_Pkw*)

The first three datasets can be subdivided again into six sets of information: four sets of emission factors for the detailed level (one for each road gradient class) and one for each of the two other levels of detail. Apart from the emission factor for CO_2 per vehicle kilometre, marked with the abbreviation "CO2(rep.)" (= carbon dioxide "reported", i.e. without the biofuel share in the fuel), the other important information given back by HBEFA is the amount of fuel used per vehicle kilometre ("mKr" = Masse Kraftstoff). This information will be of great importance for the calculation of the well-to-tank emissions which will be discussed below.

The cold start emission factor data is the same for all levels of detail. Also here the amount of fuel consumed per start is included and used further on. The data from HBEFA, which is a Microsoft Access database, can be exported as Microsoft Excel files.

5.1.2.3. Electricity consumption of the electric car

For the conventional cars HBEFA holds emission and consumption values covering the fuel types gasoline, diesel, natural gas, liquefied petroleum gas and E85. For the electricity consumption of electric cars, however, no information that detailed exists. HBEFA does not hold information on electric cars as it is only considering direct emissions and the electric car has none in this category. Due to the low number of electric cars available at this point, only a limited amount of series production vehicle exist leading to a lack of detailed consumption data.

The IFEU institute published in 2011 a baseline report on the environmental balance of electric mobility (UMBReLA). In the course of this project a life cycle assessment tool called eLCAr (E-Mobility Life Cycle Assessment Recommendations) was developed, modeling the electricity consumption and the environmental impact of the energy supply as well as the production of the vehicles. The energy consumption is calculated from high-resolution speed profiles. To validate the results also the fuel consumption for conventional cars are modeled. A comparison of these values to results retrieved from TREMOD showed a good agreement (ifeu - Institut für Energie- und Umweltforschung Heidelberg GmbH 2011). Thus it was decided to use the available values for the electricity consumption of the electric car from eLCAr for this model.

The eLCAr model is making a distinction between three different electric car sizes and three different street types, which correspond to the traffic situations in HBEFA. The values retrieved from the UMBReLA baseline report are shown below (Table 4).

Table 4: Energy consumption in kWh/100km for different vehicle sizes and street types calculated by eLCAr

	urban	rural	highway
Electric car small	17.5	18	22
Electric car medium	21	22	27
Electric car large	25	24	26.5

The table shows that the electric car consumes the least in an urban area and most on the highway, opposed to the behavior of a conventional car. Annex 3 shows a comparison of the consumption values of the electric car, the gasoline car and the diesel car.

In the course of the UMBReLA project an online tool was developed where not only CO_2 emissions but other environmental impacts of different car types can be compared (Umweltbundesamt & ifeu - Institut für Energie- und Umweltforschung Heidelberg GmbH). This tool assumes a composition of 40 % urban, 25 % rural and 35 % highway trips. With this information average values of electricity consumption are obtained. The results are shown below (Table 5).

Table 5: Average energy consumption values in kWh/100km for different vehicle sizes calculated by eLCAr

Electric car small	20.6
Electric car medium	19.7
Electric car large	19.1

The above mentioned values are without considering additional electricity consumption due to cold starts since the available data on this topic is still sparse. For the auxiliary consumers only average values are assumed. In the UMBReLA report, however, it is emphasized that the energy consumption for electric heating and cooling can be very high. (ifeu - Institut für Energie- und Umweltforschung Heidelberg GmbH 2011)

Having the aggregated traffic situations that correspond to the HBEFA values covered for the electric car electricity consumption, the question still remains how to obtain energy consumption values as detailed as the 276 traffic situations in HBEFA. An extensive modeling of these values in the course of this thesis would not be conducive for time reasons. However, a simplistic approach should be applied to ensure the completeness of the model. The chosen method is to compare the energy consumption of the electric car to the fuel consumption of a reference vehicle (Table 6).

Table 6: Ratio between consumption values of the electric car and a gasoline reference car

Type of electric car	Electricity consumption [kWh/100 km]	Type of gasoline car	Fuel consumption [L/100 km]	Ratio
Electric car small	19	Gasoline car small, Euro 6	6.1	3.11
Electric car medium	19.5	Gasoline car medium, Euro 6	7.4	2.63
Electric car large	20.4	Gasoline car medium, Euro 6	10.1	2.02

Using the ratio between the electricity consumption in kWh/100km and the fuel consumption in L/100km, the HBEFA data for the reference value is adapted applying the following assumption:

$$C_{electric}\,[kWh] \approx C_{gasoline}\,[g] \times K$$

$C_{electric}$: electricity consumption of the electric car

$C_{gasoline}$: fuel consumption of the reference gasoline car

K: conversion factor

Since the consumption factors in HBEFA have the unit grams of fuel per vehicle kilometer, the ratios discussed above cannot be used directly. With a density of 796 g/L for gasoline and dividing the value by 100 km, the following conversion values were retrieved (Table 7). (Deutscher Wasserstoff- und Brennstoffzellen-Verband e.V.)

Table 7: Conversion values from reference vehicle to electric car energy consumption

Car size	Conversion factor K
Gasoline car small, Euro 6 → Electric car small	0.0039
Gasoline car medium, Euro 6 → Electric car medium	0.0033
Gasoline car large, Euro 6 → Electric car large	0.0025

These values were multiplied with the gasoline Euro 6 vehicle fuel consumption values from HBEFA to obtain energy consumption values of the electric car for all traffic situations and four different gradient classes. In doing so the existing dataset of four Microsoft Excel files was supplemented by a fifth one, consisting of six different sheets; four for the different gradient classes, one for the medium level of aggregation and one for the high level of aggregation.

- Emission factors for electric cars (*Elektroauto*)

Due to the already mentioned contrasting behavior of electric vehicles and combustion engine vehicles in different traffic situation, this assumption for the electricity consumption does not model real life correctly. It only gives rough estimates but the model cannot be used to analyze which detailed traffic situation is most energy consuming for the electric vehicle. This fact has to be kept in mind for the further analysis. Another limitation is that only full electric vehicles are considered. Hybrids or electric cars with range extender are not included. This is due to the missing literature values.

5.1.3. Well-to-tank emission factors

To estimate well-to-tank emissions the values from ProBas is used. The types of fuel for which the well-to-tank emissions are needed result from the vehicle types covered by HBEFA. Table 8 shows the chosen processes and the corresponding emission factors from ProBas. To match the units of the emission factors given back from HBEFA which is grams of CO_2 per gram of fuel, the values from ProBas had to be recalculated. To do so the heating value and the conversion value from TJ to kWh (1 TJ = $2.8\text{x}10^5$ kWh) are needed (Deutscher Wasserstoff- und Brennstoffzellen-Verband e.V.). The following equation shows how the calculation is done.

$$EF_{recalc.}[\text{g CO2/g fuel}] = \frac{EF_{Probas}\ [\text{g CO2/TJ fuel}]}{2.8 \times 10^5\ \text{kWh/TJ}} \times H[\text{kWh/kg}]$$

$EF_{recalc.}$: recalculated emission factor

EF_{ProBas}: emission factor from ProBas

H: heating value

Table 8: Well-to-tank emission factors from ProBas (GEMIS)

Fuel type	Value from ProBas [g CO2/TJ fuel]	Heating value [kWh/kg]	Calculated value [g CO2/g fuel]	Name of the ProBas process
Gasoline	14345	11.6	0.599047152	Benzin-mix-DE-2010 (inkl. Biokraftstoffe)
Diesel	10649	11.8	0.452369484	Diesel-Mix-DE-2010 (inkl. Biokraftstoffe)
E85	24100	7.4 (Ethanol)/ 11.6 (Gasoline)	0.677731007	TankstelleBio-EtOH-Weizen-0LUC-DE-2010/en / Benzin-mix-DE-2010 (inkl. Biokraftstoffe)
Natural gas	6872	13.0 (H-gas)	0.321609574	TankstelleErdgas-CNG-DE-2010
Natural gas/gasoline mix (1:1)	14345/6872	11.6/13.0	0.460328363	TankstelleErdgas-CNG-DE-2010 / Benzin-mix-DE-2010 (inkl. Biokraftstoffe)
Liquid gas	6856	12.8	0.315924455	Umschlag-DE Flüssiggas (Lkw)-2010

The best fitting processes from ProBas were chosen. To retrieve the desired values some adaptions have to be made:

For E85 no value was available in ProBas. Since E85 is a mix consisting of 85% ethanol and 15% gasoline, the emission factor was calculated using this ratio and the processes “Benzin-mix-DE-2010 (inkl. Biokraftstoffe)” and “TankstelleBio-EtOH-Weizen-0LUC-DE-2010/en”. For ethanol a large number of possible processes and a wide range of emission factors were available. This one was chosen since a common source for Ethanol in Europe is wheat.

The natural gas/gasoline mix is used in bi-fuel vehicles. The mixing ratio always varies depending on the driving characteristics. In this case a fix mixing ratio of 1:1 was assumed.

The electric car does not run on fuel but on electricity. As research shows, the environmental impact of electric cars highly depends on the composition of the electricity mix (ifeu - Institut für Energie- und Umweltforschung Heidelberg GmbH 2011). To take this fact into account a number of different electricity mix scenarios was constructed. Following the project design of sun2car, photovoltaic systems are one option for an electricity source. Depending on the ambient conditions and the time of day, the solar energy share of the electricity mix changes. The second source is the German electricity mix from a variety of origins. Figure 12 shows how the German electricity mix is composed.

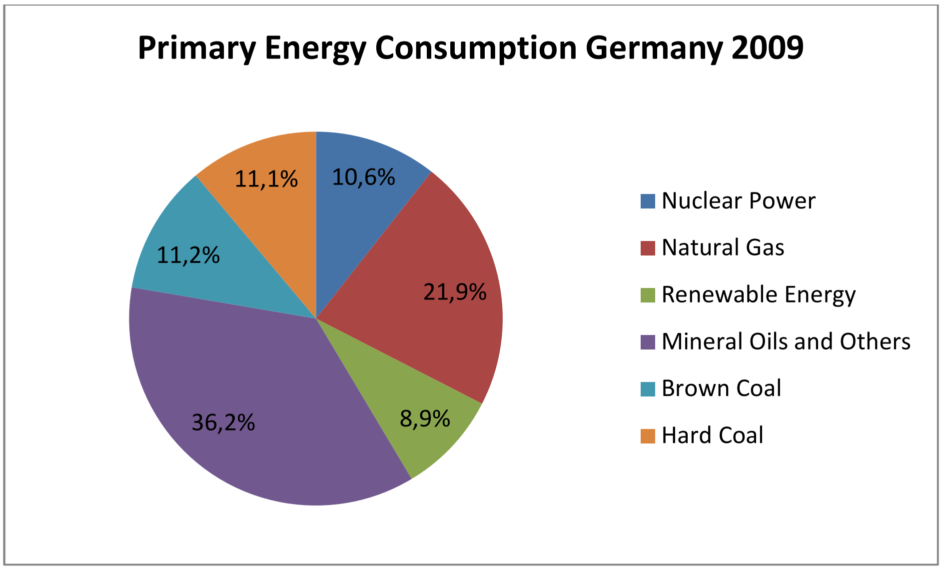


Figure 12: Electricity Mix Germany (Bayerisches Landesamt für Statistik 2011)

For the solar energy a ProBas process assuming a photovoltaic system with polycrystalline cells is chosen. This technology is most widely used due to its cost efficiency (Märtel).

As the fraction of solar energy in the overall electricity mix to charge the electric vehicle varies depending on the time of day and the hours of sunshine per day, different mixing scenarios can be possible.

Table 9 shows the constructed scenarios and the corresponding well-to-tank emission values from ProBas.

Table 9: ProBas values for electricity

Electricity scenario	Value from ProBas	Unit	Name of the ProBas process
German Electricity Mix	540.71	g CO2 /kWh	El-KW-Park-DE-2010
Solar Energy (PV)	92.32	g CO2 /kWh	Solar-PV-multi-Rahmen-mit-Rack-DE-2010
50% German Mix, 50% PV	316.52	g CO2 /kWh	calculated
25% German Mix, 75% PV	204.42	g CO2 /kWh	calculated
75% German Mix, 25% PV	428.62	g CO2 /kWh	calculated

5.2. Model construction

With all the necessary data collected, the construction of the model was started. Due to the amount of data and the complexity of the calculations that had to be carried out, programming was necessary. With the data files from HBEFA being Microsoft Excel files, the most obvious choice was to carry out the programming with VBA (Visual Basic for Applications). Below the main structure of the model and the underlying calculations are discussed. The language chosen for the model surface is German, making sure that the target users of the model do understand the instructions. All parts that are necessary to understand how the model works will be translated to English using an italic font.

5.2.1. Detailed structure of the model

With a household-based CO_2 inventory being the desired outcome the model was designed in a way that the data for all household members could be inserted in one work step. The outcome will be an overview of the CO_2 emissions of all household members including a total value for the complete household. Based on this starting position the VBA project was designed the following way (Figure 13).

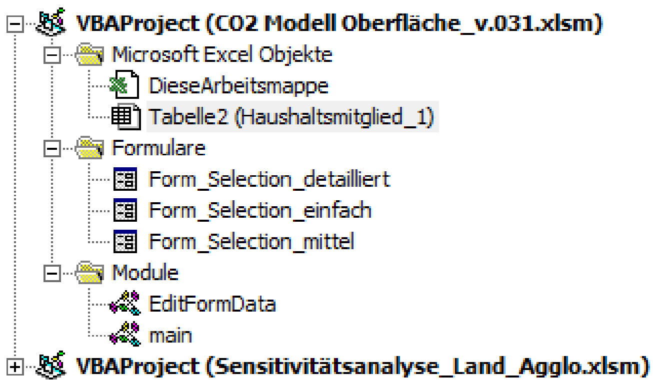


Figure 13: Structure of the VBA project

A detailed discussion of the coding will be omitted. The interested reader can find the coding with comments in Annex 4.

5.2.1.1. Workbook

The basis of the model is a Microsoft Excel workbook with a first worksheet called “Haushaltsmitglied_1” for the first household member. The user interface of this workbook is shown below (Figure 14 and Figure 15).

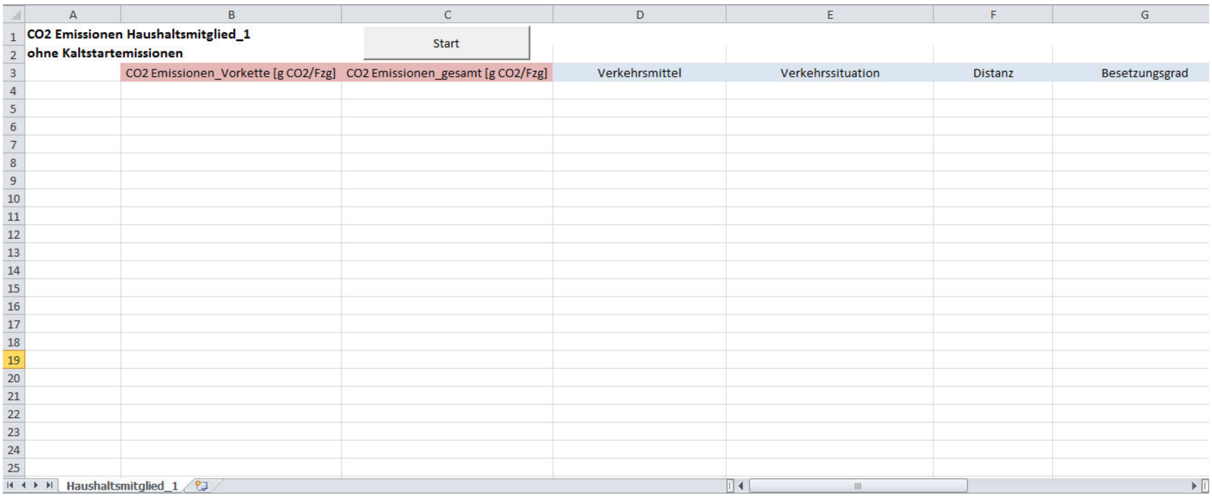


Figure 14: User interface CO2 model first part

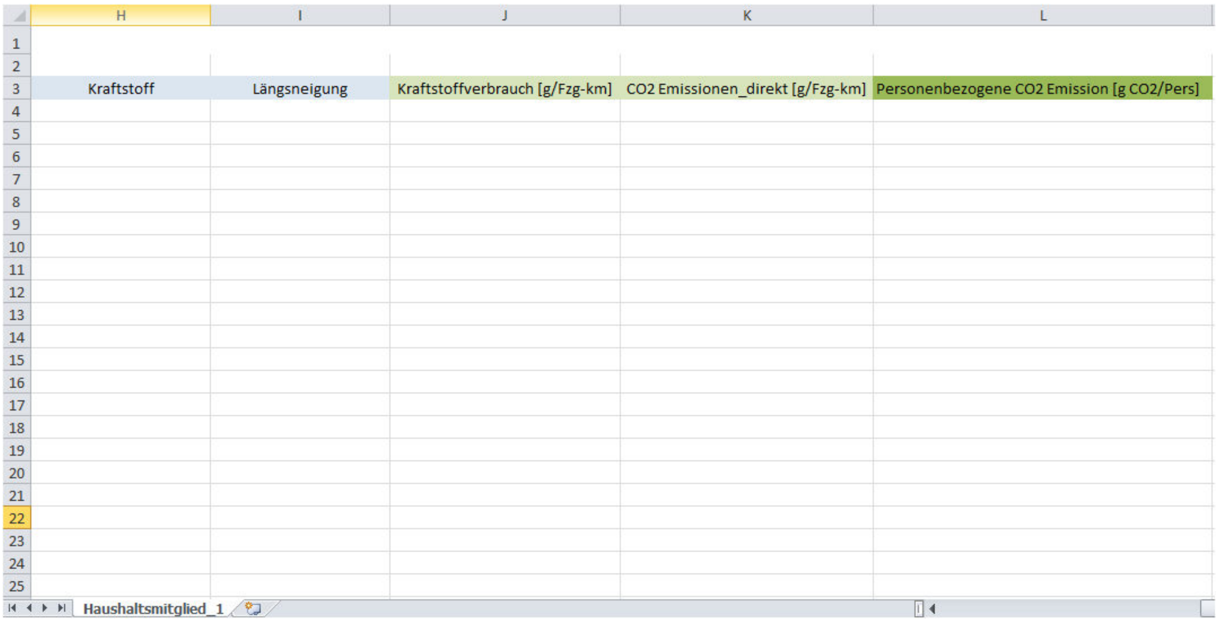


Figure 15: User interface CO2 model second part

First the CO_2 emissions of the first household member without cold start emissions are calculated. The light blue columns describe the data that has to be inserted such as mode of transport (*Verkehrsmittel*), traffic situation (*Verkehrssituation*), distance (*Distanz*), occupancy rate (*Besetzungsgrad*), fuel type (*Kraftstoff*) and the road gradient (*Längsneigung*). The light green columns hold the data that is retrieved from HBEFA on the direct CO_2 emissions (*CO_2 Emissionen direkt*) in grams of CO_2 per vehicle kilometre and the fuel consumption (*Kraftstoffverbrauch*) in grams of fuel per vehicle kilometre. The purple columns contain calculated values for the well-to-tank emissions (*CO_2 Emissionen Vorkette*) and the total (well-to-wheel) CO_2 Emissions (*CO_2 Emissionen geamt*), both in grams of CO_2 emissions but still per vehicle and not per person. Since the desired outcome is a CO_2 emission estimation for each household member, additionally the individual-related CO_2 emissions are calculate in the dark green column (*Personenbezogene CO_2 Emissionen*). These are the sum of direct and well-to-tank emissions but do not include the cold start emissions yet. The unit is grams of CO_2 per person.

Inserting the data through typing the information for each trip into the blue columns would be on the one hand time consuming on the other hand error prone. To make sure that the user only fills in the appropriate data and to increase the user-friendliness in general, an input mask was created. This input mask can be accessed by pressing the “Start” button.

5.2.1.2. Input mask

The input mask was done using a selection form in VBA. Due to the three levels of aggregation of the HBEFA data, three different input mask layouts had to be designed.

5.2.1.2.1. Simple model input mask

First the input mask for the simplest model, as shown in Figure 16, will be discussed. For the other two models the mask will be the same except for additional options to choose the traffic situations.

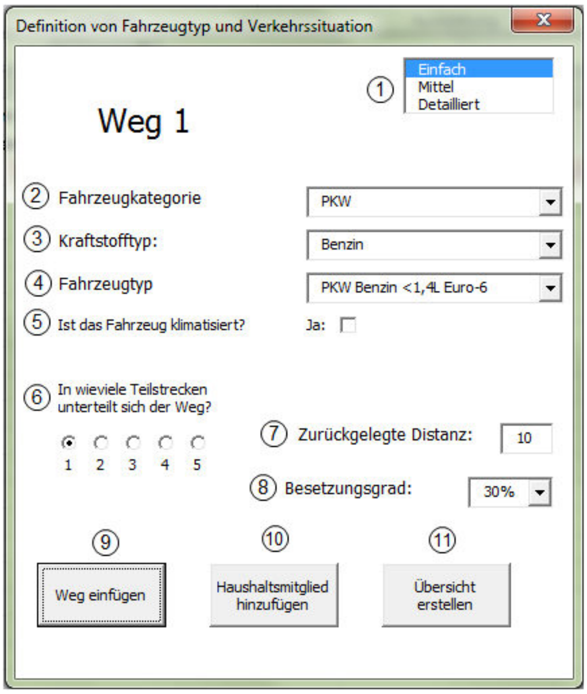


Figure 16: Input mask of the simple model

The first box (No.1) decides which level of detail is desired. Instead of the simple one (*Einfach*), a medium (*Mittel*) or high detail level (*Erweitert*) can be chosen. For the first trip (*Weg 1*) the vehicle category (*Fahrzeugkategorie*) has to be defined (No.2) which can either be a passenger car (*Pkw*), an urban bus (*Linienbus*), a motorcycle (*Motorrad*) or an electric car (*Elektroauto*). The latter could have been implemented as a passenger car with the fuel type electricity, however, defining the electric car as an own vehicle category made the programming easier. Next the fuel type (Kraftstofftyp) can be selected (No.3). To make sure that no combinations are selected that do not exist in HBEFA, the options adapt according to the previous choices. For the passenger car the following fuel options exist: gasoline (*Benzin*), diesel (*Diesel*), natural gas/gasoline mix (*Erdgas/Benzin Gemisch*), liquid gas (*Flüssiggas*) and E85. For the electric car the previously designed electricity scenarios are available: electricity mix Germany (*Strommix Deutschland*), electricity from a photovoltaic system (*Strom PV*) and three combinations of both. For the urban bus diesel and natural gas (*Erdgas*) are the fuel options. Finally the motorcycle just has a gasoline option (*Benzin*). Next (No.4) the vehicle subsegment can be selected, categorized by fuel type, size (either cubic capacity for the passenger cars and the motor cycles or tonnage for the urban bus) and emission concept. For the electric car, only a distinction between small (*Elektroauto klein),* medium (*Elektroauto mittel*) and large (*Elektroauto groß*) is made. A detailed list of vehicle subsegments and an explanation of the abbreviations used can be found in Annex 3.

The option if the car has air conditioning (check *Ja*) or not (No.5) is only available for the passenger car. The next question asks for the number of subsections of the trip (*In wieviel Teilstrecken unterteilt sich der Weg?*) (No.6). For the other two levels of detail here the traffic situation is being defined. Due to complete aggregation of all traffic situations, in this simple model the German average is used automatically. However, the occupancy rate can change throughout a trip (e.g. picking up a friend on the way to work) which is why the subsection option was kept for the simple model as well. The number of subsections is limited to the number of five, with the entry mask automatically expanding with a rising number of subsections. For each subsection the distance travelled (*zurückgelegte Distanz*) (No.7) and the occupancy rate (*Besetzungsgrad*) (No.8) are required. The occupancy rate has to be given as a percentage. This approach was applied since it is expected that for the proband it is easier to estimate the occupancy rate of a public bus by percentage than absolute number of passengers. To keep the approach consistent at the same it is asked for the motorcycle and the passenger car. Assuming the average car has 5 seats, 20% occupancy corresponds to 1 passenger, 40% to 2 passengers and so on. In case the proband is not able to estimate the occupancy rate, the default value for passenger cars is set to 30% (infas Institut für angewandte Sozialwissenschaft GmbH 2008), the one for motorcycles to 50% and the one for urban busses is set to 25% (ifeu - Institut für Energie- und Umweltforschung Heidelberg GmbH 2001). The values are the German average occupancy rates for these vehicle types.

Once the different parameters for each trip are selected the values can be inserted into the "Haushaltsmitglied_1" worksheet. This is done with the command *Weg einfügen* (insert trip) (No.9). With all trips completed a change to the next household member is possible with pressing the button *Haushaltsmitglied hinzufügen* (add household member) (No.10). To finish the calculations an overview of all family members will be compiled (*Übersicht erstellen*) (No.11).

5.2.1.2.2. Medium model input mask

Choosing the medium model in the first box the entry mask automatically adapts (see Figure 17). The only thing that changes from the simple model is one additional drop-down box which holds the street type (*Straßentyp*). The options here are the German average for highway (*Autobahn*), urban (*innerorts*) and rural (*außerorts*) street types.

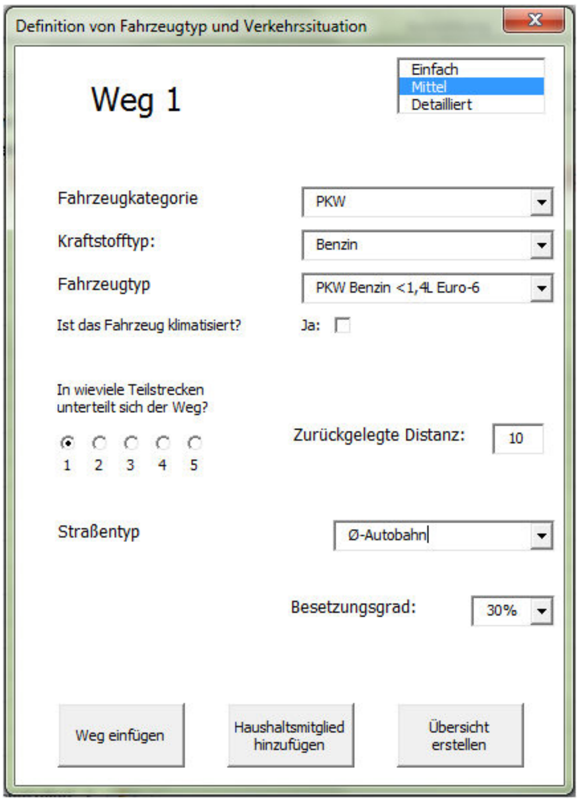


Figure 17: Entry mask of the medium model

5.2.1.2.3. Detailed model input mask

The detailed model's entry mask then looks the following way (Figure 18):

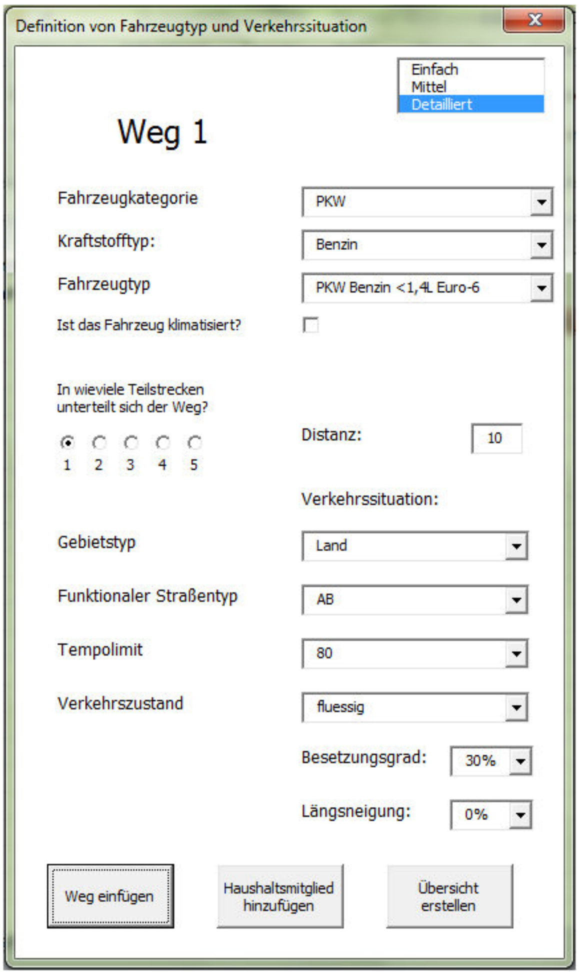


Figure 18: Entry mask of the detailed model

All traffic situations (*Verkehrssituationen*) available from HBEFA were implemented. First an area (*Gebietstyp*) has to be selected, then the street type (*Funktionaler Straßentyp*). Furthermore a speed limit (*Tempolimit*) and a level of service (*Verkehrszustand*) are necessary to define the traffic situations. A detailed description of the possible traffic situations was done in chapter 5.1.2.1.

One further additional parameter for the detailed model is the road gradient (*Längsneigung*). Four different options are here available (0%, ±2%, ±4%, ±6%) according to the data obtained from the HBEFA database.

5.2.1.3. Basic calculations

After inserting the data the model calculates in a first step the CO_2 emissions per person without the cold start emissions (hot emissions). With applying a well-to-wheel approach the total emissions consist of the direct CO_2 emissions (tank-to-wheel) and the CO_2 emissions of the preliminary energy chain (well-to-tank).

$$E_{total} = E_{tank-to-wheel} + E_{well-to-tank}$$

$$E_{well-to-tank} = C_{fuel} \times EFA_{well-to-tank}$$

E_total: total CO_2 emissions [g CO_2/veh-km]

E_tank-to-wheel: tank-to-wheel CO_2 emissions from burning of the fuel [g CO_2/veh-km]

E_well-to-tank: well-to-tank CO_2 emissions from the life cycle of the fuel [g CO_2/veh-km]

C_fuel: consumption of fuel [g fuel /veh-km]

EFA_well-to-tank: well-to-tank emission factor for the fuels [g CO_2/g fuel]

The total CO_2 emissions per vehicle kilometre can thus be calculated. However, the unit is not the desired one. Looking at one individual and this individual's trips in a sum, the unit aimed for is grams per person. To get this value the total CO_2 emissions per vehicle kilometre have to be multiplied with the distance travelled per analysed period and divided by the number of passengers.

$$E_{total\_pers} = \frac{E_{total} \times d}{OR \times n_{total}}$$

E_total_pers: total CO_2 emissions [g CO_2/pers]

d: distance [km]

OR: occupancy rate [%]

N_total: total number of seats of the vehicle

It has to be noted that the emission factors from HBEFA per vehicle kilometre assume a constant average number of 1.25 passengers per passenger car plus luggage resulting in a loading of 95kg per car (Graz University of Technology 2009). To be exact the emission factor would change with higher loads. According to the HBEFA Handbook, however, the impact of the load on the emission factor is only important for heavy duty vehicles and will thus not be considered for the passenger car (INFRAS 2010). For the urban bus HBEFA does provide emission factors for different loadings, for the sake of simplicity a loading of 50% is assumed.

To make the programming simpler the cold start emissions are only calculated when creating the overview of all household members. The cold start values that HBEFA gives back are emission factors per start (every start not only cold start). Here the assumption is made that every new trip means a new start for the vehicle. The next question is how to allocate the cold start emissions to the different passengers. A decision was made to calculate an average occupancy rate for each trip and split the cold start emissions into the average number of passengers. As well as the hot emissions the cold start emissions are divided up into direct emissions and well-to-tank emissions. The calculations are done the same way as above.

$$E_{total\_cold} = E_{tank-to-wheel\_cold} + E_{well-to-tank\_cold}$$

$$E_{well-to-tank\_cold} = C_{fuel\_cold} \times EFA_{well-to-tank}$$

E_total_cold: total cold start CO_2 emissions [g CO_2/start]

E_t-t-w_cold: cold start tank-to-wheel CO_2 em. due to higher starting emissions [g CO_2/start]

E_w-t-t: well-to-tank CO_2 em. from the life cycle of the additional fuel [g CO_2/start]

C_fuel: additional consumption of fuel per start [g fuel /start]

EFA_w-t-t: well-to-tank emission factor for the fuels [g CO_2/g fuel]

To get the CO_2 emissions per person, the total CO_2 emissions from cold start are divided by the number of passengers per trip.

$$E_{total\_cold\_pers} = \frac{E_{total\_cold}}{OR_t \times n_{total}}$$

E_total_cold_pers: total cold start CO_2 emissions per person [g CO_2/pers]

d: distance [km]

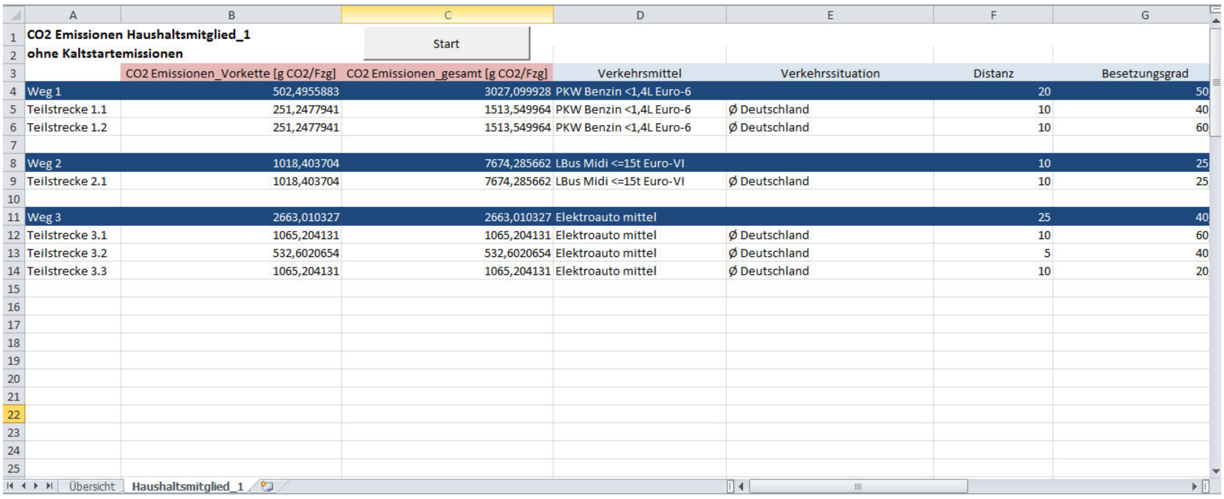
OR: occupancy rate of the trip [%]

N_total: total number of seats of the vehicle

To obtain the total CO_2 emissions per household member, all hot and cold start emissions over all trips done in the analysed period have to be summed up. The total amount per household is retrieved by adding the results for all household members.

5.2.1.4. Output of the results

Using the equations above, the results are calculated and given back in the worksheet of the household member (without cold start emissions) and the overview of all household members (with cold start emissions). The household member sheet can look the following (Figure 19):



CO2 Emissionen Haushaltsmitglied_1
ohne Kaltstartemissionen

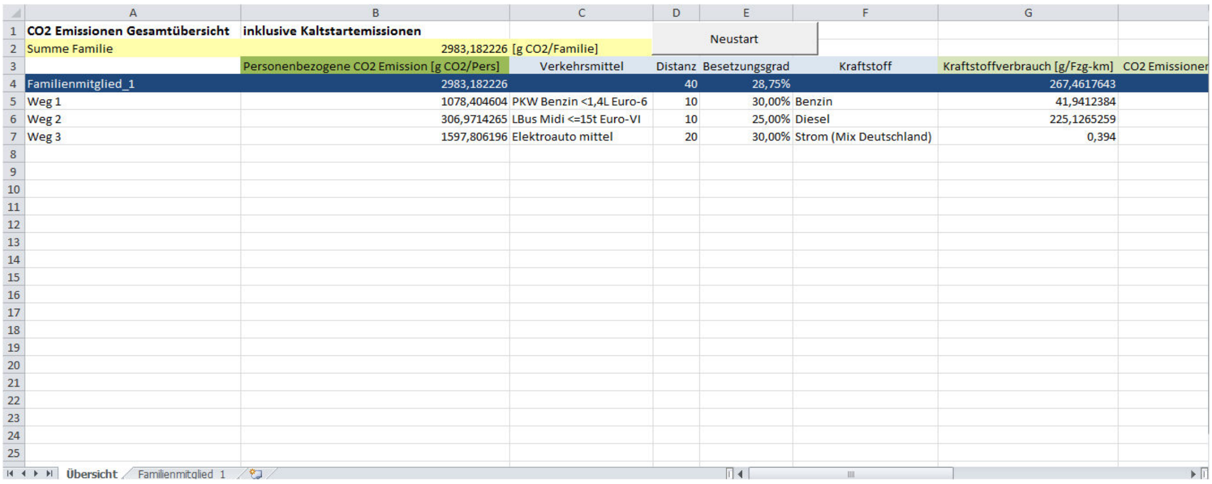
Start

	CO2 Emissionen_Vorkette [g CO2/Fzg]	CO2 Emissionen_gesamt [g CO2/Fzg]	Verkehrsmittel	Verkehrssituation	Distanz	Besetzungsgrad
Weg 1	502,4955883	3027,099928	PKW Benzin <1,4L Euro-6		20	50
Teilstrecke 1.1	251,2477941	1513,549964	PKW Benzin <1,4L Euro-6	Ø Deutschland	10	40
Teilstrecke 1.2	251,2477941	1513,549964	PKW Benzin <1,4L Euro-6	Ø Deutschland	10	60
Weg 2	1018,403704	7674,285662	LBus Midi <=15t Euro-VI		10	25
Teilstrecke 2.1	1018,403704	7674,285662	LBus Midi <=15t Euro-VI	Ø Deutschland	10	25
Weg 3	2663,010327	2663,010327	Elektroauto mittel		25	40
Teilstrecke 3.1	1065,204131	1065,204131	Elektroauto mittel	Ø Deutschland	10	60
Teilstrecke 3.2	532,6020654	532,6020654	Elektroauto mittel	Ø Deutschland	5	40
Teilstrecke 3.3	1065,204131	1065,204131	Elektroauto mittel	Ø Deutschland	10	20

Übersicht | Haushaltsmitglied_1

Figure 19: Model output: family member

For every subsection of the trip results are calculated. The overview then sums up the subsection result into one emission value per trip and then further adds all values per household member and all household members per household as shown below (Figure 20).



	A	B	C	D	E	F	G	
1	CO2 Emissionen Gesamtübersicht	inklusive Kaltstartemissionen		Neustart				
2	Summe Familie	2983,182226	[g CO2/Familie]					
3		Personenbezogene CO2 Emission [g CO2/Pers]	Verkehrsmittel	Distanz	Besetzungsgrad	Kraftstoff	Kraftstoffverbrauch [g/Fzg-km]	CO2 Emissioner
4	Familienmitglied_1	2983,182226		40	28,75%		267,4617643	
5	Weg 1	1078,404604	PKW Benzin <1,4L Euro-6	10	30,00%	Benzin	41,9412384	
6	Weg 2	306,9714265	LBus Midi <=15t Euro-VI	10	25,00%	Diesel	225,1265259	
7	Weg 3	1597,806196	Elektroauto mittel	20	30,00%	Strom (Mix Deutschland)	0,394	

Figure 20: Model output: Overview

Now that the results are calculated for the whole household, the input data should be revised again. If an error is detected the input data can easily be changed just by pressing the Start button in the family member sheet affected. If all parameters are correct a new calculation can be started by pressing the reset button (*Neustart*). The system will now ask where to save the current household data. The presetting for the storage location is a folder called “CO_2 Modell” on the Desktop. This folder has to be created beforehand and all the necessary data files for running the model have to be stored there (see the manual in Annex 5). To change this location, the programming code has to be adapted. The relevant part of the code is marked (Annex 4).

5.2.2. Possibilities to expand the model

The model as it was developed here is focused on the specific problem definition of the sun2car project in GAP. Thus the model can only be applied to similar cases. The following chapter should present options to expand the model so it can be used for a wider range of purposes.

CO_2 emissions are not the only emissions from transportation that have negative environmental impacts. Other local and global pollutants as well pose a threat to the environment and human health. Thanks to the extent of the HBEFA database, a number of other important components such as nitrogen oxides, particulate matter or sulphur dioxide are covered. Using the exact same approach as for CO_2 the necessary emission factors can be obtained. The only exceptions are the emission factors for hydrocarbons that have to be supplemented by evaporation emission factors. These additional emissions have to be added to the hot and cold emission factors. For more information on that topic see the manual for HBEFA (INFRAS 2010). As for the well-to-tank emissions, the used ProBas files for the different fuels and electricity mixes hold values for all important pollutants as well. So with rather simple adjustments and assuming that access to the HBEFA database is given, other pollutant emissions can be estimated with the presented methodology. In case more than one pollutant should be calculated at once, adjustments in the options for input parameters have to be made and the additional parameter considered in the code. For a large number of covered components it is suggested to switch from Microsoft Excel to Microsoft Access.

For the electric car the only electricity sources considered are the German electricity mix and solar energy from a photovoltaic system. For some research questions it could be interesting to investigate other electricity sources as well. To do so, the well-to-tank emission factors have to be adapted within the programming code, where exactly is indicated in the code that can be found in Annex 4. ProBas provides a large number of data sets for electricity from various different sources. Based on this data a variety of different electricity supply scenarios can be designed.

Finally the option to expand the model by rail transport should be discussed. To be able to estimate transport-related CO_2 emissions in cities which are big enough to have a subway or tramway system the inclusion of rail based transport is indispensable. Furthermore commuters that use long-distance trains should be included into the model, to be able to cover all possible daily modes of transport (water transport and air traffic are hereby excluded). For the modes that are powered by electricity the approach is similar to the one for the electric vehicle. No direct emissions occur, which means that only well-to-tank emission factors are of importance. In ProBas emission data for traction power is available (e.g. "Netz-el-DE-2010-Bahnstrom") which only leaves the question where to get electricity consumption data from. As described in the TREMOD report, data on that can be provided by the Environmental Centre of the Deutsche Bahn (DB). It has to be noted that this data is not publicly available and does not go as much into detail as the data provided for road transport by HBEFA. For municipal rail transport the data is even weaker and, from the current state of research, can only be approximated. (ifeu - Institut für Energie- und Umweltforschung Heidelberg GmbH 2010) As for the trains that run with diesel the well-to-tank emissions are well covered by ProBas (e.g. "Zug-Personen-Fern-Diesel-DE-2010-Variante1"), for the fuel consumption values again the DB Environmental Centre has to be contacted. A further source available is "Verkehr in Zahlen" (Transport in Figures) provided by the German Institute for Economic Research (DIW) that gives rough estimates for energy consumption and environmental pollution data. It becomes obvious that for the rail-based modes of transport the available data is not detailed enough to ensure a CO_2 emission analysis as detailed as it is possible for road transport. To be able to include rail transport into the model, the same level of detail of the base data should be aspired. To be able to do so the transport system of the reviewed city has to be analysed in detail and the necessary data has to be collected through further research.

As shown the model holds a range of expansion options to ensure that it can be applied to a wider range of application scenarios.

5.3. Design of the survey documents

The following section will provide information on the required input data and an exemplary questionnaire for data collection.

5.3.1. Data requirements

With the model finished, the question is how to retrieve the data to estimate and analyze the transport-related CO_2 emissions on a household level. The information required does not only include the data that is specifically required to feed the model but also some additional information that helps to interpret the results in the right context.

Which data exactly is needed to feed the developed CO_2 model is determined by the structure of HBEFA. The characterizing parameters for the different emission factors influenced the design of the model's entry mask and thus which information is required in order to be able to calculate the CO_2 emissions. Following all factors will be shortly discussed.

5.3.1.1. Mobility data

Most important for the estimation of transport-related CO_2 emissions is the collection of data on the mobility behavior of the probands.

Part of the mobility data is the mode of transport. Here the options are the conventional passenger car, an electric passenger car, a motor cycle and the urban bus. Even though not needed for the calculation, the modes by bike and by foot should be recorded as well. This is necessary to draw a complete picture of the household's mobility pattern.

In order to be able to choose the correct vehicle type from the HBEFA vehicle options, detailed information on the vehicles is needed. These include the name of the manufacturer, the exact model/type, the construction year and the power source. From this information the emission concept, the cubic capacity and the fuel type can be determined, which are the classification parameters in HBEFA. For the private vehicles this information has to be retrieved from the households directly, for public transport the data has to be obtained from the local transport company.

The trip length in km is needed to calculate the total CO_2 emissions per household and period.

For the simple model an average emission factor throughout all traffic situations is used and the collection of data on the traffic situation not needed. For the medium and the detailed model, however, the traffic situation is required. For the medium detailed model there is a distinction between three different traffic situations (urban, rural, highway), for the detailed model the number of possible traffic situations is 276, a combination of area (urban or rural), street type, speed limit and level of service (see chapter 5.1.2.1).

Since HBEFA only gives emission factors per vehicle, the occupancy rate is essential for the calculation of CO_2 emissions per household.

The gradient determines the emission factor and fuel consumption considerably, which is why it is included in the detailed model. This information cannot be retrieved from the probands since this is not common knowledge. GIS might here be the best source to determine the road gradient class.

5.3.1.2. Additional data requirements to analyze the results

The data discussed above would be enough to estimate the transport-related CO_2 of a specific household. The question is, however, what these results are used for and how detailed the following analysis is supposed to be. In any case some further information will be helpful to analyze the results properly.

Basis of every data collection of mobility behavior, is the collection of general information on the probands; the socioeconomic data. The age, the gender, the current occupation and the income level should be considered.

Even though not needed for the CO_2 emission estimation, the trip purpose is an interesting aspect for the researcher. It can give information why a certain mode of transport is being used (e.g. a car for shopping as heavy goods have to be transported). Knowledge about that can be helpful when it comes to suggesting measures to save CO_2 emissions. Thus is should be included.

5.3.2. Survey design

As discussed, there is a certain amount of information needed from the probands to be able to ensure an accurate estimation of the CO_2 emissions from transportation. In this chapter an exemplary methodology will be developed to gather all information needed. Due to the three different levels of detail for the model also the phase of the data collection will be slightly different for all three scenarios.

The software used to design the questionnaire on household and vehicle data is the system Evasys which is available at TUM. It allows both the design of an online and a paper survey. Depending on what is desired both can be obtained without additional effort.

The travel diary as the method of choice was developed in Microsoft Word due to greater design freedom.

5.3.2.1. Socio-economic data query

The socio-economic parameters chosen to be asked in the developed survey are name (1.1), gender (1.2), age (1.3), occupation (1.4 and 1.5), possession of driver's license (1.6) and the net income. The figure below shows the corresponding section from the questionnaire (Figure 21). The complete survey documents can be found in Annex 6.

The options for the occupation are:

- employed full-time
- employed part-time
- apprentice
- not employed

In case “not employed is chosen the following options are given to specify further:

- student (school)
- student (university)
- currently unemployed
- temporarily exempted
- house wife/husband
- pensioner
- federal service volunteer
- other

1. Sozioökonomische Daten

1.1 Name:

1.2 Geschlecht:
☐ männlich ☐ weiblich

1.3 Alter:

1.4 Berufstätigkeit:
☐ Vollzeit ☐ Teilzeit ☐ Auszubildende(r)
☐ nicht berufstätig

1.5 Ihre gegenwärtige Tätigkeit, wenn nicht berufstätig:
☐ Schüler(in) ☐ Student(in) ☐ zur Zeit arbeitslos
☐ vorübergehend freigestellt ☐ Hausfrau/-mann ☐ Rentner(in), Pensionär(in)
☐ Bundesfreiwilligendienstleistender ☐ anderes

1.6 Führerscheinbesitz für Pkw:
☐ Ja ☐ Nein

1.7 Wie hoch ist das monatliche Nettoeinkommen Ihres Haushalts in Euro ungefähr?
☐ bis unter 500 Euro pro Monat ☐ 500 bis unter 900 Euro pro Monat ☐ 900 bis unter 1.500 Euro pro Monat
☐ 1.500 bis unter 2.000 Euro pro Monat ☐ 2.000 bis unter 2.500 Euro pro Monat ☐ 2.500 bis unter 3.000 Euro pro Monat
☐ 3.000 bis unter 3.500 Euro pro Monat ☐ 3.500 bis unter 4.000 Euro pro Monat ☐ 4.000 bis unter 4.500 Euro pro Monat
☐ 4.500 bis unter 5.000 Euro pro Monat ☐ 5.000 bis unter 5.500 Euro pro Monat ☐ 5.500 bis unter 6.000 Euro pro Monat
☐ 6.000 bis unter 6.500 Euro pro Monat ☐ 6.500 bis unter 7.000 Euro pro Monat ☐ mehr als 7.000 Euro pro Monat

Figure 21: Questionnaire part one: socio-economic data

5.3.2.2. Vehicle data query

The information about the vehicle should hold data on: manufacturer, type/model, year of construction and the type of fuel used. The latter is a question with the pre-specified answers depending on the vehicle category. The survey questions for the passenger car are showed below (Figure 22).

2. Fahrzeugdaten

Auto 1

2.1 Hersteller:

2.2 Typ / Modell:

2.3 Baujahr / Erstzulassung:

2.4 Antriebsart:
☐ Benzin ☐ Diesel ☐ Erdgas/Benzin-Gemisch
☐ Flüssiggas ☐ E85 ☐ Elektroantrieb

Figure 22: Questionnaire part two: vehicle data passenger car

Since a lot of households have more than one car, the option to add information on each car has to be provided.

To obtain the vehicle data for the public transportation a questionnaire as well would be suitable. Interesting here is the percentage of different fuel types within the fleet, so this information can be taken into consideration for the CO_2 emission estimation later on. Basically the same questions as for the private cars have to be sent to the local transport company, only narrowing down the types of fuel to diesel and natural gas. If available also the information on an average occupancy rate should be requested as well. A draft for a questionnaire to collect the public transportation data can be found in Annex 6.

5.3.2.3. Mobility data query

The mobility data will be obtained with the help of a travel diary. The design is geared to the travel diary used for the Mobilitätspanel Deutschland (MOP) (Bundesministerium für Verkehr 2011).

5.3.2.3.1. Simple model

The simple model only uses average emission factors for each available vehicle. The data needed to be obtained by the travel diary will thus be: The trip length, the mode of transport, the trip purpose and the occupancy rate.

To make sure that the trip length is correct, not the length of the trip was asked but the starting address and the address of the place of arrival. This information has to be further processed with a geo-data management tool to obtain the exact amount of kilometers.

The options for the transport mode hold only the bus as an option of public transportation, which is expected to be the only mode available in small and medium size towns. If other modes are used they can be named under “Andere = others”, however this option cannot be calculated with the model developed here.

The occupancy rate for the car should be given through the number of fellow passengers, the occupancy rate of the bus as a percentage. Below is shown how the first column of the travel diary looks. With a new trip a new column is started.

1. Weg
Datum: ____________
Uhrzeit Abfahrt: ____________
Abfahrtsort falls nicht Heimtadresse: ________________________________ ________________________________
Verkehrsmittel: Pkw als Fahrer ☐ Pkw als Mitfahrer ☐ Elektroauto als Fahrer ☐ Elektroauto als Mitfahrer ☐ Motorrad als Fahrer ☐ Motorrad als Mitfahrer ☐ Bus ☐ Fahrrad ☐ Zu Fuß ☐ Anderes, und zwar: ____________
Falls das gewählte Verkehrsmittel ein eigenes Fahrzeug ist: Welches Modell? ________________
Uhrzeit Ankunft: ____________
Adresse Ankunftsort: ________________________________ ________________________________
Anzahl der Mitreisenden: ______ oder Besetzungsgrad des ÖPNV: ______ %

2. Weg
Datum: ____________
Uhrzeit Abfahrt: ____________
Verkehrsmittel: Pkw als Fahrer ☐ Pkw als Mitfahrer ☐ Elektroauto als Fahrer ☐ Elektroauto als Mitfahrer ☐ Motorrad als Fahrer ☐ Motorrad als Mitfahrer ☐ Bus ☐ Fahrrad ☐ Zu Fuß ☐ Anderes, und zwar: ____________
Falls das gewählte Verkehrsmittel ein eigenes Fahrzeug ist: Welches Modell? ________________
Uhrzeit Ankunft: ____________
Adresse Ankunftsort: ________________________________ ________________________________
Anzahl der Mitreisenden: ______ oder Besetzungsgrad des ÖPNV: ______ %

Figure 23: Travel diary simple model

Important in the whole procedure is that the probands document their trips without gaps. To ensure this the following explanation has to be added (Figure 24). “For the next trip please use a new column. The finish point of the last trip will be the starting point of the next one.”

Für jeden neuen Weg nutzen Sie bitte die nächste Spalte. Der Endpunkt des letzten Weges ist der Anfangspunkt des nächsten.

Figure 24: Travel diary: Additional information for the proband

5.3.2.3.2. Medium model

For the medium model the questions of the travel diary stay the same only expanded by questions on the traffic situation. The probands have to specify if the trips are in an urban area, a rural area or on the highway. As it might be difficult for the proband to estimate the length of each section, percentages should be stated. Furthermore the answer has to be supported afterwards by GIS data which ensures the exact classification of the different traffic situations.

Below a draft for the additional part of the travel diary in the medium level of detail scenario is depicted (Figure 25).

Wieviel Prozent des Weges waren Sie auf folgenden Straßentypen unterwegs?
Innerorts: ____________________%
Außerorts: ____________________%
Autobahn: ____________________%

Figure 25: Travel diary medium model

5.3.2.3.3. Detailed model

As discussed above (chapter 5.1.2.1) the detailed model holds 276 different traffic situation options. These arise from HBEFA and were fully implemented to take advantage of the high level of detail of the available data. When it comes to collecting information that specific; however, the manual travel diary reaches its limits. It will not be possible for an individual to document his travel data as specifically as the detailed model requires it. For this model type GPS tracking has to be employed. How exactly the information from driving profiles is translated into the different HBEFA traffic situations cannot be answered within this thesis. Developing a method to classify trip sections due to their speed and acceleration is possible and research is done on this topic by the TU Dresden. However, the task is quite complex and solving it exceeds by far the scope of this thesis. Thus this research gap will be left open in the hope that in the near future a tool will would have been developed to extract the necessary information from driving profiles.

5.4. Intermediate results for the model and survey documents construction

With the design of the survey documents the development of a methodology to estimate the CO_2 emissions is completed. All necessary tools, from travel diary to CO_2 emission model are ready for use. Before the methodology will be applied to the case of a proband household from the sun2car project, the sensitivity of the model will be analyzed. This analysis helps to test the model and to detect eventual weak points.

6. Sensitivity analysis

The resulting well-to-wheel emissions are influenced by a number of different parameters. To determine which parameters have the biggest influence on the results, a sensitivity analysis will be carried out. Since the emission modeling is based on data from external databases, the analysis can help to find the parameters that are most crucial for the overall results giving an idea which data should be revised to ensure correct estimations. The results also will show which input parameters are most influential, which helps to identify where measures to change the mobility behavior are most effective.

The sensitivity of the output to varying input variables can be calculated with the concept of price elasticity, a tool originating from mathematics and economics. The arc elasticity η is estimated by dividing the percentage change in output by the percentage change in the input. The percentage change is calculated relative to the midpoints of the input and output ranges. The following equation shows how the arc elasticity is being calculated. (Witzig 2011)

$$\eta_{Q,P} = \frac{\frac{Q_2 - Q_1}{(Q_2 + Q_1)/2}}{\frac{P_2 - P_1}{(P_2 + P_1)/2}} = \frac{\frac{Q_2 - Q_1}{(Q_2 + Q_1)}}{\frac{P_2 - P_1}{(P_2 + P_1)}}$$

$\eta_{(Q,P)}$: elasticity of the reviewed parameter

P_1: Value of the input parameter in the baseline scenario

P_2: Value of the new input parameter

Q_1: Output (well-to-wheel emissions) in the baseline scenario

Q_2: Output (well-to-wheel emissions) with the new parameter value

In the cases where there is not a quantitative but a qualitative change in parameter, the arc elasticity will be calculated as follows:

$$\eta_Q = \frac{Q_1 - Q_2}{Q_1}$$

The arc elasticity sheds light on the sensitivity of the output to every input parameter. The higher the absolute value of η, the higher is the influence of the parameter on the resulting CO_2 emissions. In the case of η being one, the percentage change in input parameter results in the same percentage change in output. The algebraic sign gives information if the changes of input and output point in the same direction. In the case that the magnitude of the arc elasticity is greater than one, the percentage change in output is higher than the percentage change in input. This response is classified as elastic. The opposite case, the magnitude is less than one and thus the absolute percent change in output is less than the absolute percent change in input, is termed inelastic. (Metropolitan Transportation Commission with Parsons Brinckerhoff 2013) The baseline scenario for the sensitivity analysis carried out will be the following:

Table 10: Baseline Scenario for the Sensitivity Analysis

Mode of Transport	Fuel type	Emission standard	Cubic capacity	Air conditioning	Distance	Occupancy-rate
Passenger car	diesel	Euro 6	Medium (1.4 – 2.0L)	yes	10 km	0.4

The sensitivity will be carried out for all three levels of detail of the model separately. Due to their difference in parameters, the baseline scenario has to be further defined for the parameters: gradient and traffic situation (Table 11).

Table 11: Gradient and Traffic situation for the baseline scenarios

	Gradient	Traffic situation
Simple model	Ø Germany	Ø Germany
Medium model	Ø Germany	urban
Detailed model	0%	/Rural/Motorway-Nat./80/freeflow

The gradient for both the simple and medium model is a German average. The traffic situation for the simple model is the German average as well. The medium model uses the average values for urban streets as the baseline parameter. The detailed model applies the traffic situation “rural highway” with a speed limit of 80 km/h and the traffic being in freeflow.

The baseline scenarios were chosen randomly only making sure that a high number of variations was made possible.

6.1. Sensitivity analysis of the simple model

The result for the baseline scenario of the simple model is 737.73 g CO_2/pers-km (Q1). The results of the sensitivity analysis are depicted below (Table 12). The detailed calculations can be found in Annex 7.

Table 12: Results of the sensitivity analysis for the simple model with a Q1 of 737.73 g CO2/pers-km

Varied parameter	P1	P2	Q2 [g CO2/pers-km]	η
Mode of transport*	passenger car	urban bus	261.31	0.65
Fuel type *	diesel	gasoline	981.02	-0.33
	diesel	natural gas/gasoline	759.01	-0.03
	diesel	liquid gas	779.95	-0.06
	diesel	E85	401.24	0.46
	diesel	electricity	532.60	0.28
Emission Standard*	Euro 6	Euro 5	763.70	-0.04
	Euro 6	Euro 4	823.70	-0.12
	Euro 6	Euro 3	807.10	-0.09
	Euro 6	Euro 2	1062.92	-0.44
	Euro 6	Euro 1	905.28	-0.23
Cubic capacity*	medium (1.4L - 2.0L)	small (<1.4L)	573.39	0.22
	medium (1.4L - 2.0L)	large (>2.0L)	964.38	-0.31
Distance	10.00	12.00	880.43	0.97
	10.00	14.00	1023.12	0.97
	10.00	16.00	1165.81	0.97
Occupancy rate	0.4	0.2	1475.47	-1.00
	0.4	0.6	491.82	-1.00
	0.4	0.8	368.87	-1.00
	0.4	1.0	295.09	-1.00
Well-to-tank emissions	ProBas	ProBas +20%	757.31	0.14
	ProBas	ProBas +40%	776.89	0.16
	ProBas	ProBas +60%	796.47	0.17
Tank-to-wheel emissions	HBEFA	HBEFA +20%	880.43	0.97
	HBEFA	HBEFA +40%	1023.12	0.97
	HBEFA	HBEFA +60%	1165.81	0.97
Air conditioning*	yes	no	722.41	0.02
Cold start*	yes	no	713.47	0.03

* Calculation of η with the equation $(Q_1-Q_2)/Q_1$

To interpret these numbers, the highest absolute η values should be identified. The clearly highest value is the elasticity of the occupancy rate with -1. This means the percentage change in CO_2 emissions is equal to the percentage change in occupancy rate. As all emission factors are divided by the occupancy rate in a last step of the calculation to get from vehicle kilometers to person kilometers, this result is consequential. On the other hand it means that the occupancy rate is the most crucial factor for a correct outcome. For private cars, the number of passengers should be easy to estimate, for public transportation, however, this information is difficult to obtain. To eliminate this uncertainty more in depth research should be carried out.

The occupancy rate behaves similarly to the distance. To sum up the CO_2 emissions for a certain period of time, the emission factors are multiplied by the amount of kilometers. Only the cold start emissions do not depend on the distance rather on the number of starts, which is why the absolute elasticity of the distance is lower than one.

The next important value is the data from HBEFA with a value of 0.97. It shows that the model is a lot more sensitive to the direct emission values than to the emission values of the preliminary energy chain (η = 0.14 – 0.17). This is a positive sign since the direct emissions are a lot easier to estimate and the values thus have a high certainty. The well-to-tank emission estimation, however, is a lot more complicated and thus more error prone. This result for the well-to-tank emissions has to be treated with caution though, as the baseline scenario here is a diesel vehicle. For an electric vehicle which only produces indirect emissions, the case is different. Below the results are shown for a sensitivity analysis carried out for an electric car as the baseline scenario. Using the same base settings as before (Table 10) a result of 532.60 grams of CO_2 per person is calculated as the Q_1.

Table 13: Sensitivity of the well-to-tank emissions for the electric car scenario with a Q1 of 532.60 g CO2/pers-km

Well-to-tank emissions	P1	P2	Q2 [g CO2/pers-km]	η
	ProBas	ProBas +20%	639.12	-1.00
	ProBas	ProBas +40%	745.64	-1.00
	ProBas	ProBas +60%	852.16	-1.00

As the results show, the elasticity values for the electric vehicle scenario are now -1, thus a lot higher than before. This means that the outcome is now highly influenced by the well-to-tank input data. If the model is frequently used for electric mobility emission estimations, the well-to-wheel emission values should thus be analyzed in detail and if necessary revised.

As expected, the mode of transport does have a high elasticity (η = 0.65). With the same fuel type and the same occupancy rate both systems are comparable. The result shows that switching from car to bus has a positive effect on the emissions per person kilometer.

A change in fuel type results in rather different elasticities. The highest impact has a switch from diesel to E85 (η = 0.46), followed by gasoline (η = -0.33) and electricity (η = 0.28). The model on the other hand shows a low sensitivity to a change to the natural gas/gasoline mix (η = -0.03) and liquid gas (η = -0.06). In any case, the choice of fuel is important for the outcome and if there is a switch from a fuel type with very high emissions to an opposite one, the savings in CO_2 emissions can be substantial.

Emission standards were implemented to establish threshold values for Carbon monoxide (CO), Nitrogen oxides (NO_x), Hydrocarbons (HC) and Particulate matter (PM). As CO_2 emissions are not covered by these emissions standards, the emissions class does not provide information on the amount of CO_2 emission, thus a higher Euro class does not necessarily mean a lower CO_2 emission value. This becomes clear with the non-consistent values for the elasticity, there is no clear trend observable. However, with lower Euro classes, the age of the car rises which makes a lower efficiency and thus higher CO_2 values more likely. (Umweltbundesamt 2012)

The elasticity values for the cubic capacity changes show the expected values; the larger the cubic capacity, the higher the CO_2 emissions. With values of 0.22 and -0.31 the absolute value for η ranks somewhere in the middle of the calculated values.

Both the inclusion of cold start emissions and the exclusion of air conditioning do not have significant effects on the CO_2 emission results.

6.2. Sensitivity analysis of the medium model

The baseline scenario result of the medium degree of detail model was calculated as 855.57 g CO_2/pers-km (Q1). Annex 7 shows the elasticity values for the different parameters that have been changed. As the model structure for all three models is the same, all parameters that are available in the simple model are expected to have the same elasticity values as for the other two models. The values show that this is the case. The compliance of results is furthermore a confirmation that the model is working properly.

The one parameter that does not align with the simple model is the traffic situation. The baseline option is an urban street. The results are shown below (Table 14).

Table 14: Results of the sensitivity analysis of the medium model with a Q1 of 855.57 g CO2/pers-km

Traffic situation*	urban	rural	640.90	0.25
	urban	highway	741.11	0.13

Switching to a rural street has an elasticity of 0.25, switching to the highway results in a η of 0.13. Both values are significant, thus the input information on the traffic situation should be collected carefully.

6.3. Sensitivity analysis of the detailed model

The result of 615.58 grams of CO_2 per person-kilometer was retrieved for the baseline scenario of the detailed model. The results of the sensitivity analysis can be found in Annex 7. Below (Table 15) only the parameters that differ from the other two models are depicted.

Table 15: Results of the sensitivity analysis of the detailed model with a Q1 of 615.58 g CO2/pers-km

Varied parameter	P1	P2	Q2 [g CO2/pers-km]	η
Traffic situation (level of service)*	/Rural/Motorway-Nat./80/freeflow	/Rural/Motorway-Nat./80/heavy	591.91	0.04
	/Rural/Motorway-Nat./80/freeflow	/Rural/Motorway-Nat./80/saturated	685.24	-0.11
	/Rural/Motorway-Nat./80/freeflow	/Rural/Motorway-Nat./80/stop+go	1066.84	-0.73
Traffic situation (area)*	/Rural/Motorway-Nat./80/freeflow	/Urban/Motorway-Nat./80/freeflow	586.01	0.05
Traffic situation (speed limit)	/Rural/Motorway-Nat./80/freeflow	/Rural/Motorway-Nat./90/freeflow	609.38	-0.09
	/Rural/Motorway-Nat./80/freeflow	/Rural/Motorway-Nat./100/freeflow	622.84	0.05
	/Rural/Motorway-Nat./80/freeflow	/Rural/Motorway-Nat./110/freeflow	683.22	0.33
	/Rural/Motorway-Nat./80/freeflow	/Rural/Motorway-Nat./120/freeflow	725.87	0.41
	/Rural/Motorway-Nat./80/freeflow	/Rural/Motorway-Nat./130/freeflow	773.70	0.48
	/Rural/Motorway-Nat./80/freeflow	/Rural/Motorway-Nat./>130/freeflow	860.13	-0.40
Gradient	0%	±2%	599.99	-0.01
	0%	±4%	617.72	0.00
	0%	±6%	690.93	0.06

* Calculation of η with the equation $(Q_1-Q_2)/Q_1$

As discussed above, the main parameters of all three models should match, which is the case for the detailed model as well. Only for the discrete choices some small deviations are observable. These differences stem from the approach of emission calculation in HBEFA. Since the differences are not significant, this issue will not be further analyzed.

The traffic situation options in the detailed model are numerous; in total 276 different possibilities. As analyzing each one of them would be excessive work, the focus will be on one traffic situation. One parameter at a time the variables “level of service”, “area”, “speed limit” and “gradient” will be changed. The street type stays the same since a speed limit of 80 km/h would not be available for the street type access-residential.

The range of elasticity values for different levels of service goes from 0.04 to -0.73. The latter is the highest of all η values within the traffic situation parameters. Apparently the level of service can have a high impact on the outcome. This is specifically important if the proband is hitting rush hour every day to go to work. Information on this should be collected, which for this level of detail is only possible with GPS. Whether the vehicle is driving in a rural or in an urban area has little impact on the outcome (η = 0.05).

The speed limit shows with rising elasticity values the higher the speed limit gets. With values up to 0.61 for η, this parameter highly impacts the outcome. Just as the level of service this information has to be retrieved through GPS tracking to ensure the data is sufficiently detailed.

Finally, the model shows a low sensitivity to the road gradient. When collecting the data with GPS tracking the information on road gradients should be available as well. However, calculating the gradients could result in a high amount of work. Given the low elasticity values it could be considered to leave the gradient out (using 0%) or to estimate one gradient class for the whole area of investigation.

6.4. Sensitivity analysis of all three models

A further interesting point to evaluate is how the level of detail of the models influences the results. For this purpose one trip in a rural area and one trip in an urban area are compared. As there is a wide range of traffic situations for the detailed model to choose from, the traffic situation with the lowest and with the highest emission factor, are considered. The basic parameters are the same as used above (Table 10). The table below shows the chosen traffic situations and the corresponding results (Table 16).

Table 16: Sensitivity analysis of different degrees of detail

	Model	**Traffic situation**	**Result [g CO_2/pers]**
Scenario 1 (urban)	detailed	/Agglo/AB-City/70/fluessig	561.00
	detailed	/Agglo/Erschliessung/50/stop+go	1,340.55
	medium	urban	855.57
	simple	Ø Germany	737.73
Scenario 2 (rural)	detailed	/Land/FernStr/60/fluessig	580.90
	detailed	/Land/Erschliessung/50/stop+go	1,340.55
	medium	rural	640.90
	simple	Ø Germany	737.73

The numbers show that the results differ significantly from one level of detail to the other. While the difference between the results of the medium and the simple model is 117 g CO_2/person for the urban scenario and 97 g CO_2/person for the rural scenario, the difference of the detailed model to the other two models depends on the traffic situation. The span of the results for the detailed model between the traffic situation with the lowest and the highest emission values is 780 g CO_2/person for the urban scenario and 760 g CO_2/person for the rural scenario. This range is significantly large and shows that in the most extreme cases, the CO_2 emissions can be overestimated by 52% or underestimated by 52% when using a model with aggregated traffic situation values. While for national inventories it can be argued that the different traffic situation values even out taking the whole country into consideration, the same does not apply for micro scale applications. On the micro scale, certain traffic situations can dominate and an average over all traffic situations, as used for the simpler models, would then distort reality. Consequently the model choice highly influences the outcome especially when “extreme” traffic situations are the case. To obtain the most realistic values in a micro scale application, the traffic situations should be considered and thus the detailed model should be applied. Using that model not only measures like switching modes of transport or fuel types can be analyzed, but also options like taking a different route to avoid certain types of streets or traffic jams.

6.5. Results of the sensitivity analysis

The sensitivity values can be divided into the ones resulting from quantitative changes and the ones from qualitative changes. To illustrate the sensitivities for the quantitative parameters, the changes in output were plotted against the changes in parameter which is depicted below (Figure 26). As discussed above, all three models show similar elasticity values for all the parameters that coincide. This is why the figure is valid for all three models, except for the speed limit which is only a parameter of the detailed model.

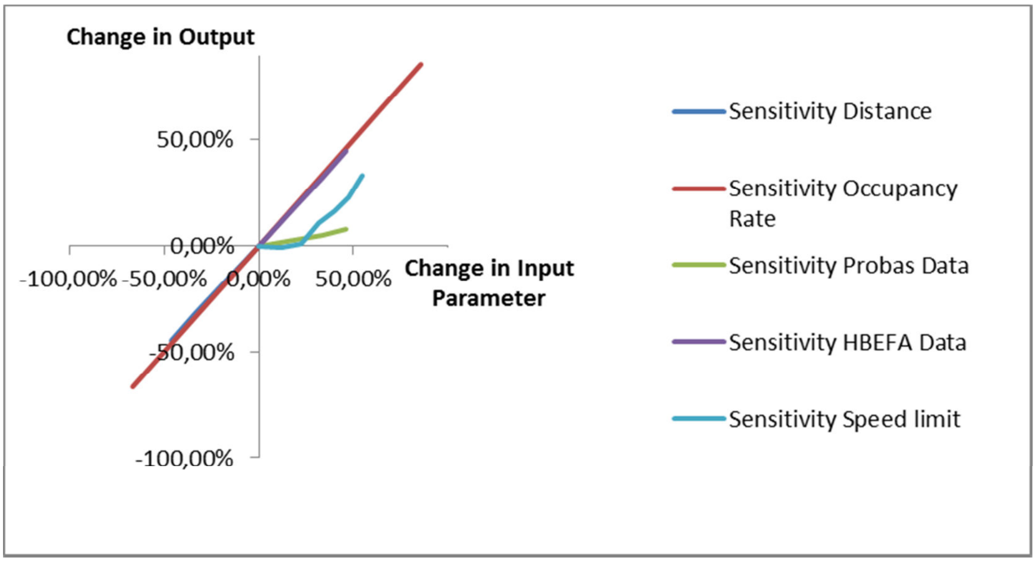


Figure 26: Sensitivities for the detailed model

To be able to compare all parameters, the algebraic sign of the results for the occupancy rate was changed, all other parameters remain untouched. With the elasticity being the ratio between the change in input parameter and the change in output, it matches the slope of the graphs showed above. The steeper the curve, the higher the sensitivity of the model is towards the parameter. Looking closely, the occupancy rate is identified to be the most important parameter, closely followed by the HBEFA data and the distance, which is not visible due to the high alignment of the elasticity of these two parameters. Next comes the speed limit and then last the ProBas Data.

Interesting here is that all parameters except for the speed limit show a linear effect, meaning that the changes in outcome are directly proportional to the changes in input parameter. For the speed limit, however, this does not apply. Here the graph shows an exponential increase.

From the parameters that change qualitatively, the fuel type, the mode of transport and the cubic capacity are important for all three models. The emission standard gets more important the older the car is. The traffic situation turned out to be a crucial parameter as well. With elasticity values up to -0.73 the driving pattern can have a high influence on the resulting CO_2 emissions and should not be neglected if possible.

For the model, these results mean it is a lot more sensitive to the underlying emission data from HBEFA than ProBas. Different is the case for the electric car, without direct emissions the outcome is highly dependent on the ProBas data for the well-to-tank emissions. If the model is used for an in depth analysis of electric mobility, the well-to-tank emission factors should be revised. Due to the complexity of the well-to-tank process chain the values can vary significantly.

As for the input parameters, the occupancy rate, the distance, the mode of transport and for the detailed model, the traffic situation can have a high impact on the outcome. Measures to increase the occupancy rate, to decrease the distance and changes in mode of transport and traffic situation will lead to the best CO_2 emission savings.

A comparison of the results calculated by all three levels of detail of the model showed that the impact of the model choice highly impacts the outcome. To ensure the most realistic results the detailed model should be applied.

7. Application of the methodology to the sun2car scenario

With the methodology now being fully developed it should be applied to a specific case. Since up to now no empirical data from the project was available, generic data will be used to go through the example step by step. Sun2car, the research project already discussed and currently being carried out by the TUM, will be used as orientation. In the project, households in Garmisch-Partenkirchen (GAP) living in a one family house that have an already existing photovoltaic system will be provided with an electric car from Audi. With GPS tracking the mobility behaviour of the whole household will be recorded and the CO_2 emissions from transportation will be estimated. Through the app, the probands will be informed about their CO_2 emissions and get propositions on how to lower their emissions. Following data from the "Mobilität in Deutschland" (MiD) surveys and the Federal Motor Transport Authority (KBA) will be used to construct a realistic scenario.

7.1. Construction of a typical GAP family storyline

First a representative storyline for a one-family household in GAP has to be developed. Being the most detailed and extensive survey on mobility behaviour, MiD is the data source which most likely holds all the information necessary. To be able to analyse the large amount of data that had been collected, a tool was developed called "Mobilität in Tabellen" (MiT). It is publicly available on the the MiD homepage and provides the data for different parameter combinations in tabular form. (Bundesministerium für Verkehr 2013c)

7.1.1. Basic data from MiD

As the mobility behaviour is highly dependent on whether a proband is living in a rural or urban area, the results were sorted after the municipality size. With 26,000 inhabitants GAP lies in the available range of 20,000 to 50,000 inhabitants. Following average values for different parameters such as kilometres travelled per day or number of trips per day are presented based on the MiT data (Table 17). Furthermore the values used in the example developed here are presented. These differ a little form the original values since only one household will be analysed and the number of trips is limited, thus the MiD data has to be rounded up or adapted a little. The original tables these values are based on can be found in Annex 8.

Table 17: Average MiD values versus used values

Parameter	Rounded value from MiD	Values used in the example
Number of cars per household	2	2
Number of trips per day	3.5	3.5
Kilometres travelled per person per trip	11	9.8
Kilometres travelled per person per day	38	37.5
Overall travel time per person per day [Min]	74	88.9

Furthermore information is available on the modal split (Table 18), the trip purpose (Table 19) and average speed values for the different modes of transport (Table 20). Again these are values for the municipality size 20,000 to 50,000 inhabitants.

Table 18: Modal split from MiD versus example

Mode of transport	Values from MiD	Values used in the example
By foot	22.60%	14,29%
Bike	12.40%	14,29%
Motorised private transport (passenger)	16.00%	14,29%
Motorised private transport (driver)	43.10%	42,86%
Public transportation	5.90%	14,29%

Table 19: Trip purposes from MiD versus example

Trip purpose	Percentage	Values used in the example
Work	13.50%	14.29%
Business trips	6.00%	0.00%
Education	6.20%	28.57%
Shopping	21.30%	14.29%
Errands	12.40%	0.00%
Leisure	32.00%	28.57%
Accompanying	8.60%	14.29%

Table 20: Average speeds per mode of transport from MiD

Mode of transport	Speed [km/h]
By foot	4.4
Bike	10.8
Motorised private transport (passenger)	29.8
Motorised private transport (driver)	30.4
Public transportation	25.3
Not specified	40.7

7.1.2. Storyline

Following the model will be calculating results for different storyline scenarios. The baseline scenario will display an average day in a four person household. This baseline is based on average MiD data for a family living in a municipality the size as GAP. Further on the electric car as a measure to lower CO_2 emissions will be introduced. Since it is not predictable how the introduction of an electric car will impact the family's mobility behaviour, different scenarios will be considered. Out of the data presented above a storyline for a four person household was developed. Basic assumptions were that the family consisted of the parents and a son and a daughter. To map an average day, a normal workday was chosen. The family owns two cars (German average for this household size). The father is commuting to work, the mother is a stay-at-home mum. The son is the older one of the kids going to high school seven kilometres far away, the daughter still in primary school has to travel only one kilometre. According to the MiD averages the number of trips, the distances and travel times were chosen. Furthermore the mode of transport and the trip purposes were selected in a way they mirrored as closely as possible the average values. Due to the small number of family members, replicating the MiD values exactly was not possible. This, however, was not necessary since the example should demonstrate the procedure rather than give an exact estimate for the CO_2 emissions of a GAP household. Below the developed basic storyline is displayed (Table 21).

Table 21: Basic Storyline

Time	Trip purpose	Distance [km]	Passengers	Mode of transport	Speed [km/h]	Duration [Min]
07:15 - 08:14	Father travels to work	30	Father	Main car	30.4	59
07:30 - 07:44	Daughter travels to school	1	Daughter	By foot	4.4	14
07:25 - 07:42	Son travels to school	7	Son	Bus	25.3	17
12:10 - 12:24	Daughter travels home from school	1	Daughter	By foot	4.4	14
13:10 - 13:27	Son travels home from school	7	Son	Bus	25.3	17
15:00 - 15:20	Mother brings son to soccer practice	10	Mother, son	Second car	30.4	20
15:25 - 15:35	Mother travels to the mall	5	Mother	Second car	30.4	10
16:15 - 16:25	Mother travels from the mall to the soccer field	5	Mother	Second car	30.4	10
16:30 - 16:50	Mother brings son home	10	Mother, son	Second car	30.4	20
17:00 - 17:59	Father travels home from work	30	Father	Main car	30.4	59
19:00 - 19:33	Father travels to the gym	6	Father	Bike	10.8	33
20:30 - 21:03	Father travels home from the gym	6	Father	Bike	10.8	33

7.1.3. Vehicle data

The vehicle data was retrieved from KBA data on the most commonly used cars in Germany (Kraftfahrt-Bundesamt KBA 2013). For the main car a Mercedes E-Klasse and for the second car a VW Golf are realistic choices. To classify the cars, the year of construction (to retrieve the emission class), the fuel type and the cubic capacity are necessary. This information can be retrieved from the technical datasheet provided by the manufacturer (Mercedes Benz; Volkswagen). Here the fuel type is assumed to be Diesel for both cars and the Euro standards are chosen randomly.

Mercedes E-Klasse:

- Fuel type: Diesel
- Cubic capacity: > 2.0 L
- European emission standard: Euro V

VW Golf:

- Fuel type: Diesel
- Cubic capacity: 1.4L – 2.0L
- European emission standard: Euro IV

For the public busses the transportation company in GAP was contacted. The following data on the busses in service was made available (Table 22).

Table 22: Vehicle data public busses in GAP

Amount	Manufacturer	Year of construction	Fuel type	Emission standard	Maximum permissible gross laden weight kg
7	Mercedes O 530 Citaro	2003	Diesel	Euro 3	17400
4	MAN A21 Lion's City	2012	Erdgas NG	EEV	17800

The most frequent bus type is the Diesel Mercedes Citaro and was thus used for this example. The necessary data was again retrieved from the technical data sheets of the manufacturer (Mercedes Benz).

- Fuel type: Diesel
- Tonnage: 15 – 18t
- European emission standard: Euro III

Also average occupancy rates were requested form the transportation company in GAP. Since there were none available the German average of 25% was applied. It has to be noted that during rush hour the occupancy rate could be significantly higher. Since the son is traveling to school and back, he will hit the rush hour. Due to the lack of data no other values than the German average can be applied. This data inaccuracy, however, will be kept in mind for the analysis later on.

7.2. Calculation of the results

The calculation of the CO_2 emissions will be done with the simple version of the model. Without concrete mobility data, using a model with a higher level of detail would be with speculation. It has to be kept in mind though, that for such a micro-scale application the traffic situation might have a considerable impact.

Following the results for the baseline scenario will be calculated. Subsequently, some of the parameters that had to be assumed for the baseline scenario are being varied to show what effect they have on the outcome. Furthermore a range of measures to lower CO_2 emissions will be discussed. All detailed calculations can be found in Annex 10.

7.2.1. Results baseline scenario

The results for the baseline scenario retrieved from the simple are shown below (Table 23).

Table 23: Results for the baseline scenario

Family member	Emissions [g CO_2 /person and day]
Father	11,992.43
Mother	3,255.99
Son	2,256.99
Daughter	0.00
Sum:	**17,505.41**

As the table shows, the result for the whole family is 17.5 kg of CO_2 per day. This rather abstract number should now be compared to literature values.

MiD delivers results on CO_2 emissions per km, which were retrieved with TREMOD. A calculated average value for the household and municipality sized is 94.3 grams of CO_2 per person kilometre. The total amount of travelled kilometres by the example household is 150 which leads to a sum of 14,100 grams of CO_2 per household. This and the result displayed above lie closely together, considering that the four-person household is not a specific option in MiD. For the value above an average over four different household-types was calculated (See Annex 9). Applying the highest value of the range (112.6 g CO_2/km) the result would be 16,890 grams of CO_2 per household; even closer.

This comparison shows that the values retrieved from the developed model lie in a realistic range. Still, the absolute amounts of CO_2 emissions are lacking expressivity. More informative would be an analysis how changed parameters impact the outcome.

7.2.2. Results for the electric car scenarios

Within the sun2car project half of the proband households will receive an electric car. As it cannot be foreseen how the implementation of an electric car will influence the mobility pattern of the example household, a number of different scenarios were constructed.

The most realistic scenario would be that the electric car substitutes the second car. Due to the limited range of the electric car the probands could feel uncomfortable to use the electric car for longer distances. Thus, the car will be used for short trips within the town of GAP that were done before by the second car. All other modes of transport are assumed to stay the same. How this storyline will look is depicted in Annex 9.

In the optimistic scenario the following assumption is taken as a basis: taking part in a research project on electric mobility, the probands' awareness of the environmental impacts of their mobility has increased. To minimize the CO_2 emissions the father is using the electric car to commute to work and the son travels to soccer practice by bus, instead of being brought there by his mother. She instead uses the supermarket nearby to make her errands taking the bike. Annex 9 displays such an optimistic storyline.

Of course there are multiple possible versions to decrease the CO_2 emissions even further (e.g. increasing the occupancy rates by giving co-workers a lift), however, a moderate optimistic scenario should be applied just to show CO_2 emission saving potential due to small changes in daily habits.

The pessimistic scenario works from a different angle. The probands are taking part in the research project and getting an electric car for free. What if the family takes advantage of this "free" car (the electricity still has costs, however they are rather negligible) and substitutes zero emission and low emission trips (bike/foot and public transportation) by the electric car? Annex 9 shows how a pessimistic scenario could look like.

The implemented electric car is an Audi A1 E-tron car with range extender. Due to its weight and battery capacity it was classified a medium size electric car (ifeu - Institut für Energie- und Umweltforschung Heidelberg GmbH 2011). The fact that the car has a range extender was neglected, since the battery holds enough energy for 50 km (von Maydell 2012). The longest trip done by a household member in the scenario designed here is 30 km, assuming that possibilities to recharge the vehicle exist at the workplace, the range extender is not needed. Thus the vehicle can be assumed to be a fully electric car. For the electricity a 50/50 mix of German grid electricity and solar energy was assumed.

Below the results for the three different electric car scenarios are shown in comparison with the baseline scenario (Figure 27).

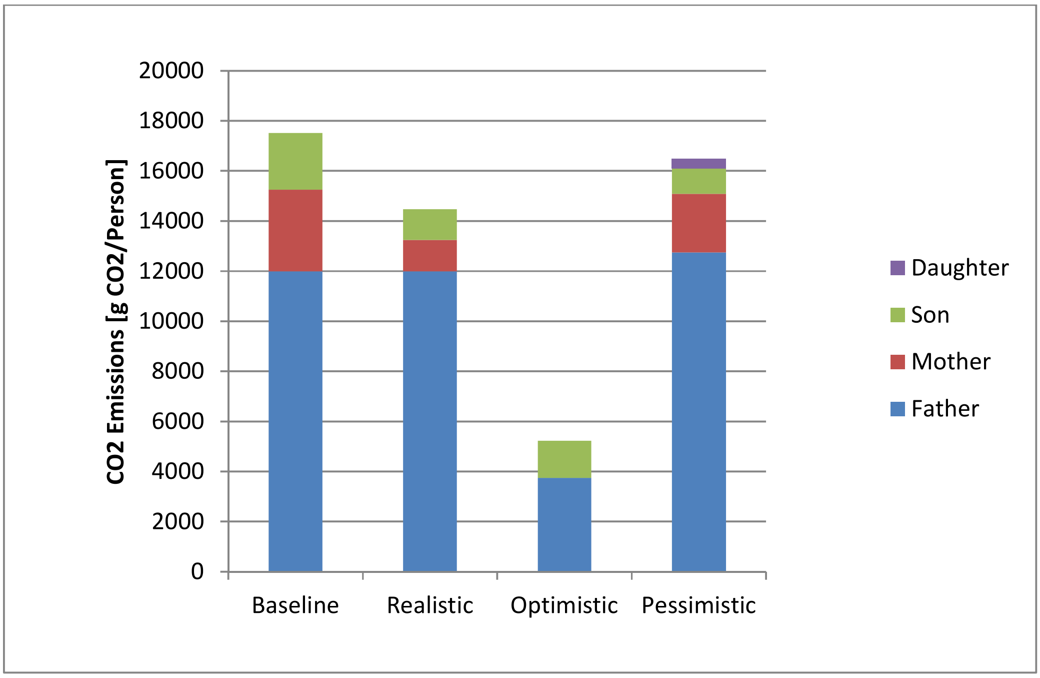


Figure 27: Comparison of CO2 emission results for all scenarios

As the results show, the implementation of the electric car leads to a reduction of CO_2 emissions in every case. However, the absolute reductions vary significantly depending on the assumed scenario. The realistic scenario shows a 17% reduction. Even though it is significant, the optimistic scenario results in only one third of the original value. When several emission reduction measures go hand in hand the CO_2 emission reduction is very effective. The pessimistic scenario on the other hand displays that implementing a new measure can have effects opposed to what was wanted and results in savings lower than expected (only 6%). Although these scenarios are purely speculative the values show that emission reduction measures cannot be considered in isolation. The process of making mobility decisions is too complex as it could be exactly foreseen how a new measure changes the mobility behavior. Empirical data will show in which range the values lie within in reality.

7.2.3. Results for different changed parameters

Following some parameters will be changed for either the baseline or the realistic electric car scenario to show what impact they can have on the final outcome. This is only a selection of possible measures; in reality the variety of possible options is endless.

For the above presented scenarios a number of assumptions had to be made due to the lack of information. Following a number of these parameters should be tested to estimate if the effect of a variation is significant and would thus call for a more into depth investigation.

7.2.3.1. Different occupancy rate of public transportation

As discussed already there were no occupancy rates available for the public busses and a German average of 25 had to be applied. Following it will be investigated how assuming an occupancy rate of 80% for the rush hour will impact the outcome (Figure 28).

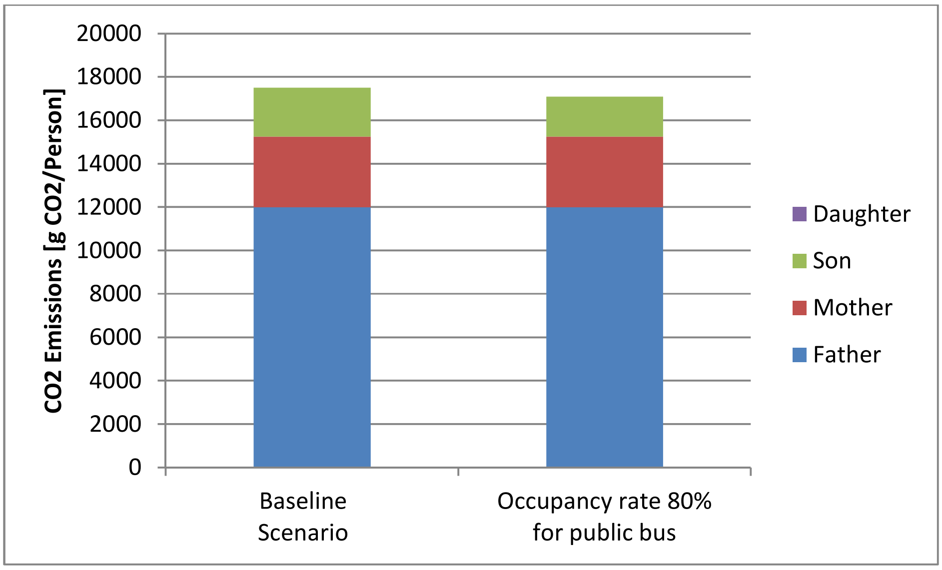


Figure 28: Changed occupancy rates in public bus applied to the baseline scenario

While the absolute CO_2 reduction for the whole household is not very significant (2.4%), the reduction of CO_2 emissions for the son is not negligible (18.6%). If the percentage of public transportation for the whole family was higher, the impact of the occupancy rate in public busses would be strong. Consequently, it is very important to have exact occupancy rate values; otherwise the results will be highly distorted.

7.2.3.2. Change of public bus from diesel to natural gas

As stated by the local transport company, four out of 11 public busses run with natural gas. For the baseline scenario only the diesel vehicles were considered. To see if the type of fuel used by the public busses has an influence on the total CO_2 emissions all bus trips were replaced with a 15-18t CNG bus. The results obtained are shown below (Figure 29).

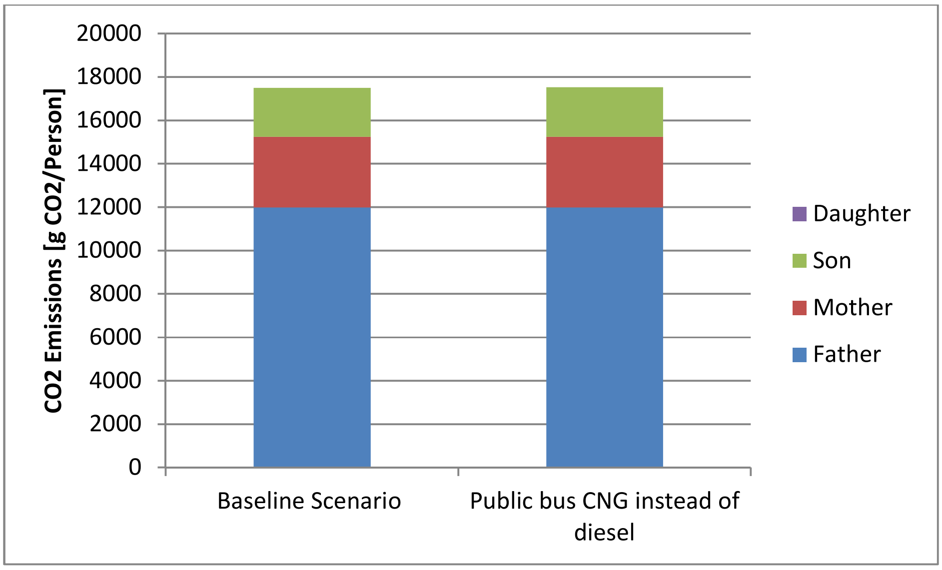


Figure 29: Changed fuel type for public bus applied to the baseline scenario

Other than expected, the CO_2 values do not decrease but increase by 0.1%. A closer look at the values shows that while the well-to-tank emission values are lower for CNG than for diesel, the well-to-wheel emission factor per vehicle kilometre is higher. As previously mentioned, a conversation with the HBEFA developer showed that the natural gas values are not based on a high number of empirical data. To make sure that these values are reliable, they should be revised again.

7.2.3.3. Different electricity mixes

For the electric car scenarios, so far a mix of 50% energy from a photovoltaic system and 50% German grid mix was assumed. As one of the objectives of the sun2car project is to investigate how the electricity composition changes the CO_2 emissions, a comparison of the different electricity mixes was done for the realistic electric car scenario (Figure 30).

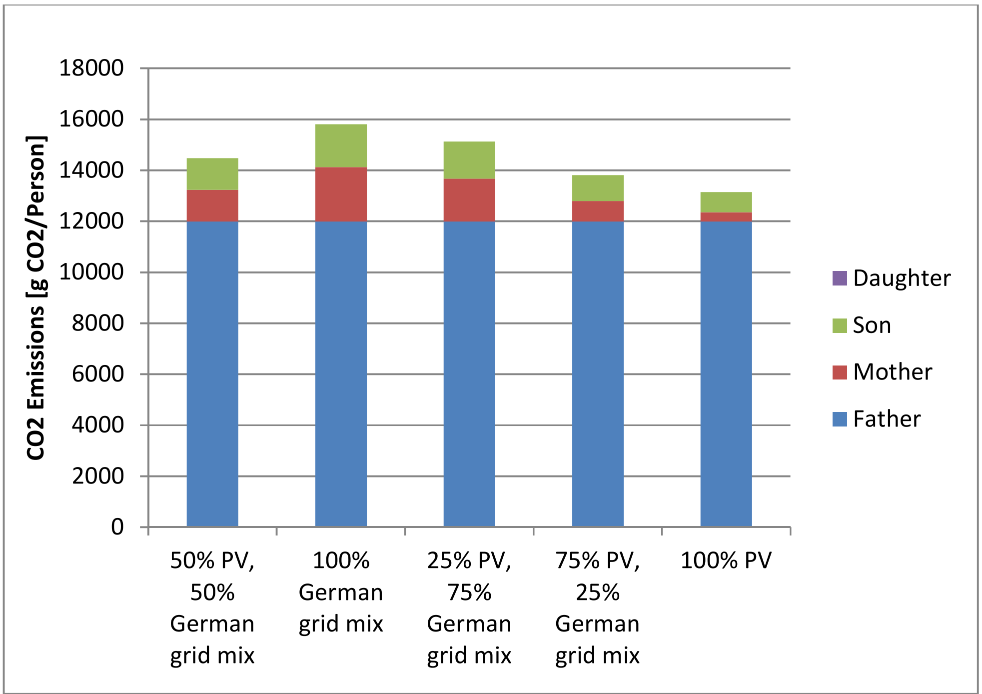


Figure 30: Results for different electricity mix scenarios applied to the realistic scenario

The results show that the values can differ up to 17% from German grid mix to 100% solar energy. So there is a significant impact of the energy mix on the CO_2 emission outcome. One might have expected even higher differences between the two energy sources. These results are controlled by the ProBas values for the energy sources. While solar energy as a renewable energy source is considered an environmentally friendly energy source, the production of the photovoltaic systems is still highly energy consuming. This is reflected in the rather poor CO_2 emission advantages. To ensure that the emission reduction potential is fully exploited, the production process of the photovoltaic system has to be investigated, and the least CO_2 producing process strived for.

Other energy sources should be considered as well. Wind and hydropower have an even better CO_2 balance and can be accessed by purchasing green electricity.

7.2.3.4. Different occupancy rates for the private vehicles

As shown with the results of the sensitivity analysis (chapter 6), the occupancy rate is a parameter that highly influences the person-related CO_2 emissions. How this effect shows will be demonstrated with the baseline scenario. While public transportation occupancy rates cannot be changed by the individual, the private car occupancy rates can be influenced. For both private cars separately the results are shown below (Figure 31).

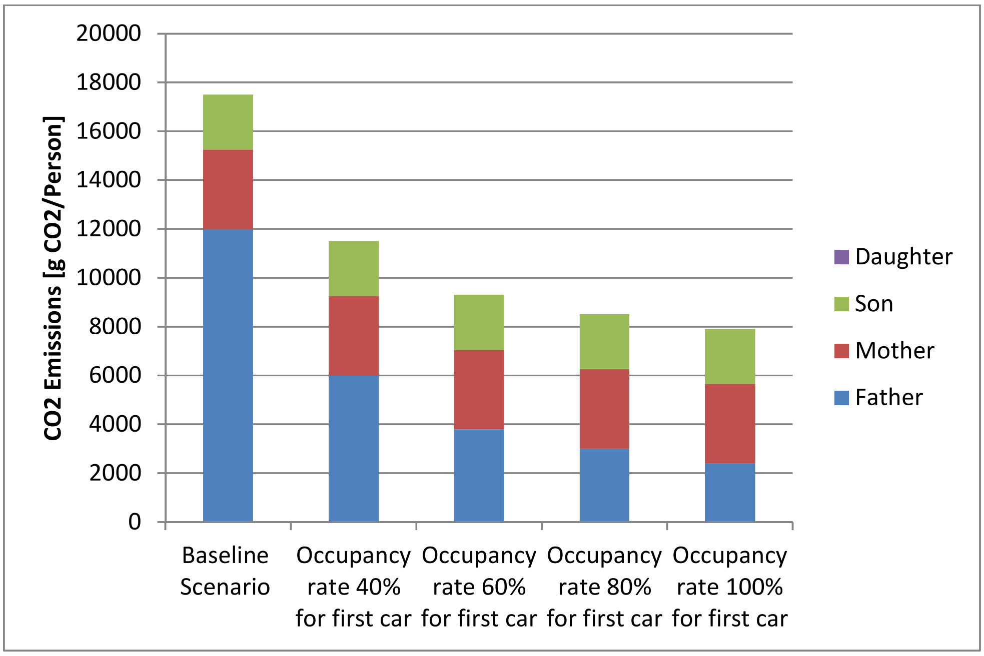


Figure 31: Changed occupancy rates for the first car applied to the baseline scenario

With the father's trip to work contributing most to the total CO_2 emissions of the household, a change in occupancy rate for these trips results in a significant decrease in emissions. Up to emission savings of 55% are possible. While other parameters such as for example the distance cannot easily be changed, the occupancy rate would be a very simple measure to decrease emissions. Car-pooling could be organized through work or the internet (e.g. Mitfahrgelegenheit.de is a widely used platform).

Also the occupancy rates of the second car in the family can be improved. A very realistic scenario could be that other children attending soccer practice life on the way to the soccer field. Picking two of these kids up and bringing them back home can safe around 8% of emissions as the figure below shows (Figure 32).

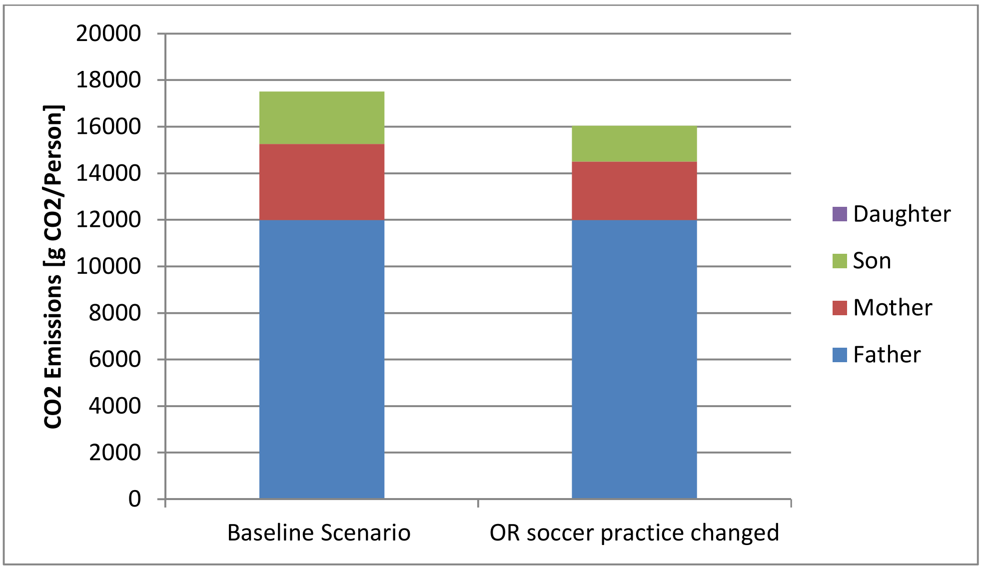


Figure 32: Changed occupancy rates for the second car applied to the baseline scenario

As the results show, changing the occupancy rate of the private vehicles proved to be a very effective and easily implemented measure for CO_2 emission reduction. If the model was used to suggest measures for immediate CO_2 reductions, the change of occupancy rate would be one of them.

Apart from the occupancy rate there are other short-term CO_2 reduction measures which will be shortly discussed but not calculated.

One option would be a switch from CO_2 intensive modes to more environmentally friendly modes. How this could look like was shown with the optimistic scenario, with several switches at once. The result showed that there is great potential of CO_2 savings especially when short trips are done with emission free transport modes.

Also a result of the sensitivity analysis was the finding that travel distances are almost proportionally linked to the CO_2 emissions. Here some savings could be made; however, trips to work, school or practice are predetermined and cannot be influenced (short-term) by the individual.

How changes in traffic situation impact the CO_2 emissions would be another parameter interesting to investigate. While the sensitivity analysis showed that the influence can be significant the question remains if the traffic situation can be considered a parameter that can be influenced by the individual. With modern technology congestion can already be detected to a certain extent and alternative routes can be suggested. Also information technology that indicates eco-friendly driving behavior is already available. In combination, these tools could be used to find for each trip the route with the least CO_2 emitting traffic situations. The potential and the feasibility of such an approach should be investigated empirically. A theoretical assessment of possible savings could be carried out with the detailed version of the model.

A rather long term solution, nonetheless of interest is the change of the private vehicles. Already demonstrated was the switch from a conventional diesel vehicle to the electric car. Not only the propulsion technology has an impact on the CO_2 emissions but also the cubic capacity does.

7.2.3.5. Different cubic capacities

For the baseline scenario it was assumed that the first car the father is using to commute to work is a car of the biggest cubic capacity. It could be questioned if this cubic capacity is really necessary. As Figure 33 and Figure 34 show a change in car could reduce the CO_2 emissions drastically.

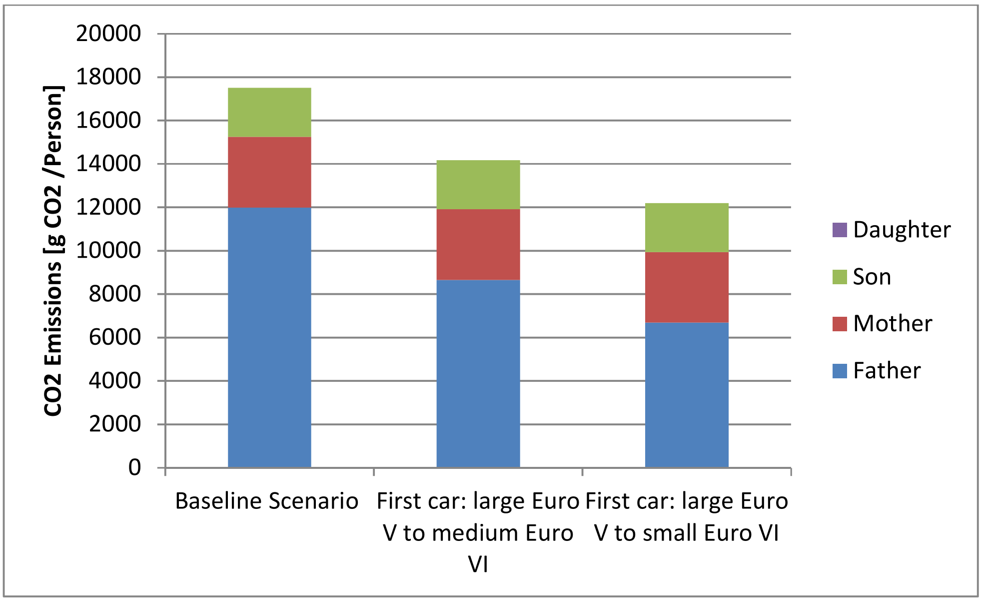


Figure 33: Different cubic capacities for the first car applied to the baseline scenario

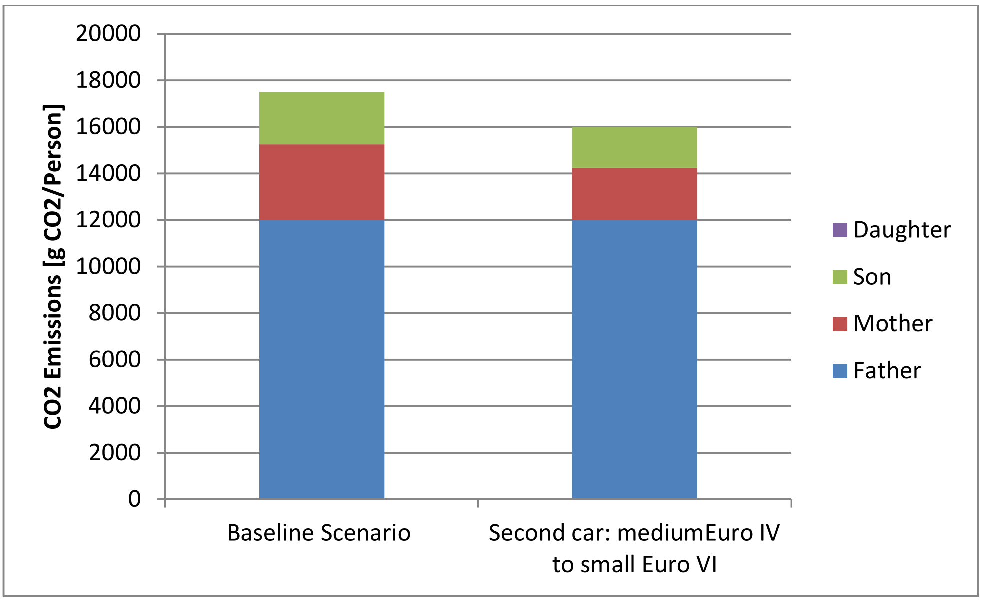


Figure 34: Different cubic capacities for the second car applied to the baseline scenario

For the first car two options and savings up to 30% compared to the baseline scenario are possible. For the second car, due to its overall smaller contribution, the savings are around 9%.

7.3. Interpretation of the results

A first comparison of the results for a baseline scenario with literature values showed that the values lie in a realistic range. As the values are rather abstract, a number of parameters were changed to demonstrate how effective different CO_2 reduction measures are and how differences in assumptions can impact the results. As all the changes were made in regard of the exemplary storyline of a GAP household, the CO_2 reductions are depending on the specific mobility pattern. This means that the results show which measure would be effective in this specific case but do not indicate which one of the parameters is the absolute most effective one (this was done with the sensitivity analysis in chapter 6). An example here is public transportation. Due to its low share of the overall mobility, a change in occupancy rate or propulsion technology only leads to small changes in CO_2 emissions. For the private vehicles the case is the opposite. Even small changes in occupancy rate or cubic capacities yield high CO_2 emission reductions. Putting a focus on the private vehicles is indispensable do to its share of almost 60% of all transport modes for a town size like GAP. Shifting individual motorized transport to public transportation and emission-free transport modes such as walking and biking show very good results as the optimistic scenario demonstrated. Also an increase in occupancy rate proved to be a simple but effective measure.

A more long-term measure is improving the private vehicle. Switching to a smaller car can have significant impacts on CO_2 emissions as was demonstrated above. When looking into a switch in private vehicle also other propulsion technologies should be taken into consideration. Electric cars being on the rise, this option was investigated in detail. Due to the applied well-to-wheel approach the electric car is not as emission-free as it is commonly advertised. The results show that there is a reduction effect but the resulting well-to-tank emissions are still significant. But even though the electric car is not emission-free it should be kept in mind that CO_2 emissions are not the only environmental impact from transportation. While the emissions from the electricity production are considerably high, the local noise and pollutant emissions are almost zero for the electric vehicle. This example shows that looking only at CO_2 might be a too one-sided approach. While this CO_2 emission model can help identify hotspots in the mobility pattern of a household and can assess the effectiveness of CO_2 reduction measures, it cannot give universal statements on the environmental friendliness of different mobility scenarios. Other environmental categories such as acidification, aquatic and terrestrial toxicity or ozone depletion as well as local pollution have to be considered.

8. Evaluation of the methodology and need for further research

The previous chapters have shown how the methodology was developed and how it can be applied. As in every methodology, it has its strengths and weaknesses. Depending on the intended application area they can vary. A final evaluation should give an overview of which reasons speak for the methodology and which weaknesses remain. How the methodology can be improved through further research will be discussed in the following.

8.1. Evaluation

To be able to judge how meaningful the results are and how good the applicability of the model developed here is, the strengths and weaknesses of the model are discussed below.

8.1.1. Weaknesses of the methodology

Due to the exclusion of rail transport, the model is limited to small and medium sized towns. This restriction of the scope of application was done for reasons of time pressure and the fact that the specific application this model was designed for did not require a rail transport inclusion. To ensure, however, the maximum range of applications the model should be expanded. A suggestion of how this could be done was given in chapter 5.2.2.

A further weakness of the model is the manual input of the data. Based on travel diaries as a starting point, a manual input is inevitable. The travel diary is only a suitable mobility data collection method for the simple and medium model. In case of the detailed model, the traffic situation data would have to be collected via GPS. Analysing the driving profiles and inputting the information by hand would be impractical and rather time consuming thus an interface to automatize the input needs to be developed. This further leads to the problem that the connection between driving profiles and HBEFA traffic situations is not covered with this thesis. Even though this topic is under investigation in research, a publicly available solution has not been developed yet. Consequently, the detailed version of the model can, at this point in time, only be used through manual characterization of driving profiles or for theoretical analyses.

Also limited by the current state of research is the implementation of the electric car scenario. With the commercial use of electric cars being an upcoming trend of the recent years, the empirical data on the behaviour of these vehicles is still limited. While the energy consumption values used for the simple and medium model are based on concrete values calculated within the UMBReLA project, the detailed model consumption values are based on simple assumptions. This approach might give results that allow to roughly compare the electric vehicle with other modes of transport, however it is not suitable for detailed comparisons of different traffic situations. This is due to the electric vehicle behaving antipodal to the conventional vehicle when it comes to consumption values in different situations. While stop and go traffic for example is not a problem for the electric vehicle due to the recuperation of energy during the breaking process, the conventional vehicle has the highest fuel consumption for this type of traffic situation. To be able to analyse in detail the behaviour of the electric vehicle this model is not suitable. A detailed modelling of the energy consumption would be indispensable, this lies however out of the scope of this study.

Additionally the electric car scenario only includes full electric cars in three sizes. Hybrid cars or electric cars with range extender are not considered due to the lack of available data.

8.1.2. Strengths of the methodology

It was intended to develop a methodology that can be widely applied without expensive technology and high costs. Using the travel diary as the mobility data collection method of choice this was ensured.

A further advantage of the CO_2 model over existing emission models for transportation is that unlike the commonly used models, the model presented here was developed for a micro-scale inventory and not for a large scale application. As a consequence the output is scaled to CO_2 emissions per person/household and can be directly used without further calculations. This way, calculation efforts are minimized.

Furthermore the models currently available are often very complex. TREMOD is even not publicly available due to this complexity. For inexperienced users the handling of these models might be overwhelming. For the model developed here the aim was to design the model as clearly as possible, leading to a simple model structure. Even though the model is intended to be used by experts, with some guidance even the general public would be able to use it.

Also an advantage of the model is the fact that it includes very detailed data. Especially the detailed version of the model goes very deep. This way specific parameter variations can be investigated which helps to identify where the largest CO_2 saving potentials lie. This information can then be used to suggest efficient CO_2 reducing measures.

The fact that the user gets to choose between different levels of aggregation for the model makes sure that an adaption of the model to different application scenarios is possible. Depending on the mobility data collection options that are available and the desired detail of results the model can be modified. This ensures versatile application options.

The model was designed in a way that not only CO_2 emissions can be estimated with this methodology. With simple adjustments (see chapter 5.2.2) of the model all the emissions from other pollutants and GHG that are covered by HBEFA can be estimated. This is specifically interesting for pollutants that, unlike CO_2, are not directly correlated with the fuel consumption. Using the HBEFA emission factors these more complex emission estimations are covered.

A last advantage is the fact, that the model is only based on Microsoft Excel. No additional software is required, which not only saves some costs, but also makes sure that the user is already familiar with the basic functions of the program and has no fear of contact.

8.1.3. Intermediate results of the model evaluation

Most of the presented weaknesses of the model arise from the simplification of available traffic emission models and the current state of research which is insufficient to answer all the open questions that arise from this specific thesis problem. While the limitations of the model concerning the area of application can be annulled by expanding the model by rail transportation, the electric mobility questions can only be answered with further research. Given the importance of electric mobility for the Federal Government and the number of research projects covering this topic, significant progress can be expected in the next couple of years. Meanwhile the model developed here is a tool for detailed analysis of conventional transport and rough estimations of differences between electric mobility and the conventional modes.

8.2. Need for further research

The methodology as it stands now is suitable for practical CO_2 emission assessments for short time periods using aggregated traffic situation emission factors. The detailed version of the model can only be used for theoretical assessments, due to the research gap concerning the treatment of driving profiles and the fact that a long term assessment of traffic situations that detailed cannot be done manually. To be able to fully take advantage of the detailed data provided by HBEFA an approach has to be developed on how to assign traffic situations to the different sections of a driving profile. Developing an exact and robust approach is expected to require intensive research. To prevent too high research efforts, synergies with other universities should be made use of. As the manual input of data for the detailed model is impractical, an interface between driving cycle data and the model developed here is needed.

A further weakness of the detailed model is the simplified assumptions for the electric car consumption values. In order to accurately differentiate between the detailed traffic situations a modeling of the electricity consumption for the electric car is necessary. Here the eLCAr of the ifeu institute might be a suitable tool and cooperation should be pursued.

In order to be able to apply the methodology to cities where rail transport is an option for daily travel additional research has to be carried out. While well-to-tank emission values for railway electricity are available the consumption of different rail transport modes is not documented sufficiently. A look into the modeling approach of TREMOD showed that the assumed consumption values were not backed up with a lot of detailed data (ifeu - Institut für Energie- und Umweltforschung Heidelberg GmbH 2010). Due to the diversity in rail transport modes the data basis is rather weak. To obtain accurate consumption values the transport system might have to be analyzed individually for each city. Furthermore, since the driving cycles of rail transport do not match the ones of road transport, a methodology has to be developed on how to define traffic situations.

Depending on the individual research question, more into depth analysis of some parameters is needed. To use the model to assess the CO_2 emission potential of alternative transport modes other than a fully electric car additional research has to be carried out. Even though HBEFA covers bi-fuel vehicles, E85 and liquid gas, according to Infras the values are not highly reliable and should be investigated further. One approach for fuel cell vehicles is presented in the UMBReLA report.

For electric vehicles a detailed analysis of the electricity mix might be interesting. Depending on the state, the grid mix compositions can vary significantly. Figure 35 shows how the Bavarian grid mix is composed compared to the German grid mix.

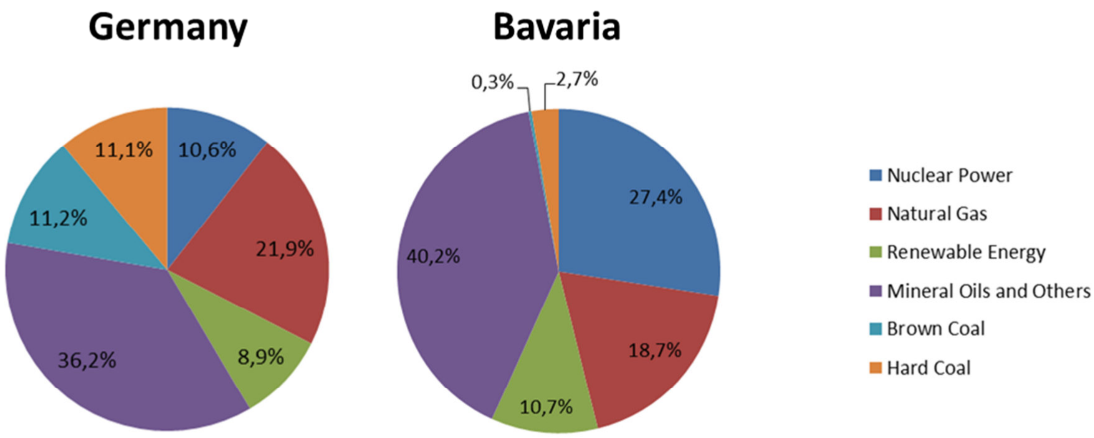


Figure 35: Grid mix comparison Germany and Bavaria (Bayerisches Landesamt für Statistik 2011)

A further point of interest could be a comparison of the grid mix and “green” electricity or the analysis of future grid scenarios. While some future grid mix scenarios are covered by life cycle databases, the state-specific electricity composition is not well documented and further research is needed.

As shown above there are numerous options for further research in order to either optimize the model or adapt it to specific purposes. The simple structure of the model and the transparent documentation of the construction process presented in this thesis hopefully make the desired modifications of the model easily possible.

9. Summary and Outlook

In this final chapter all intermediary results of the previous chapters of the work presented here are summarised again to give a condensed overview. Furthermore an outlook should be given on the potential of the results using an empirical application.

9.1. Summary

The aim of this thesis was to develop a methodology for estimating transport-related CO_2 emissions on a household level that can be applied to the example of a proband family in the sun2car research project of Audi, TUM and the Research Centre of Energy Economics in Garmisch-Partenkirchen.

Considering the important role that individual mobility decisions have on the global CO_2 emissions, the need for a tool that estimated CO_2 emissions on a micro-level was identified. This would allow the analysis of individual mobility behaviour and the ability to test different measures of CO_2 reduction.

To introduce the subject, basic principles of CO_2 emission estimation were discussed. Introducing terms such as emission factor and activity intensity helped to structure the parameters that influence CO_2 emissions. For the emission factor different system boundaries were identified, using the material flow concepts tank-to-wheel, well-to-tank and life cycle assessment. The parameters influencing the emission factor were discussed in detail, separately for the three concepts, to give an overview of all factors that have to be taken into consideration for a comprehensive emission estimation.

To narrow down the total amount of parameters, the system boundaries for the methodology were adapted to the aspirated area of application. First the functional unit was determined as the amount of CO_2 emissions per one household for a certain period of time. Defining the geographical scope of whole Germany and a present day time horizon requiring data no older than 5 years from 2013, the boundaries were roughly drawn. Focusing on passenger transport and excluding holiday traffic, the transport modes and activities are decimated. A significant limitation of the model was determined by the decision to exclude rail transport. Since not considered of importance for the type of area the methodology will be applied to (rural area to small town), this limitation was accepted in order to save modelling efforts and to be able to do a more into depth analysis of the remaining transport modes. The resulting considered modes are the conventional passenger car, the electric car, the motorcycle and the public bus. To be able to compare the electric car to other modes of transport but keeping the modelling effort manageable, the well-to-wheel approach was identified to be the most suitable one. Finally a number of parameters that have to be included to ensure a complete emission estimation are defined, such as occupancy rate, cold start emissions and road gradients.

With the defined system boundaries of the methodology in mind a thorough analysis of existing emission models, databases and methods for mobility data collection were carried out. Existing modelling approaches such as aggregated emission factor models, average speed models, traffic situation models and modal model were identified. The most important models used for CO_2 emission estimation were found to be HBEFA, TREMOD, COPERT, TREMOVE and MOVES. A comparison of the strengths and weaknesses of these models yielded the result that the most fitting model would be TREMOD. Due to its non-availability the need to construct a new model was recognized. The HBEFA database provides the necessary tank-to-wheel emissions. For the well-to-tank emissions LCA databases must be used. A comparison of available LCA data sources resulted in deciding for the ProBas database of the Federal Environmental Agency, which holds a collection of LCA data from a number of different sources.

The two main methods to collect mobility data are the travel diary and the tracking of travel movements with GPS. The travel diary is the traditional way of data collection where the probands have to document manually all their trips and important characteristics for a defined period of time. While this method leads to a high amount of work for the proband and struggles with inaccuracy and incompleteness, the GPS method promises to solve these issues. With automatic tracking the survey period is not limited to a couple of days any more. The method shows great advantages for all quantitative parameters such as travel distances and travel times. However, when it comes to qualitative aspects as used transport mode or trip purpose the realization is rather complex. Even though a lot of research is being done in this field, the technology is not yet developed enough to completely substitute the travel diary. For this reason the travel diary is the method which is applied within this thesis.

As using the whole database of HBEFA would be too impractical the retrieving process for the necessary data is hence described in detail. Covering the needed transport modes passenger car, motorcycle and public bus, all modes except for the electric car are already available. Providing emission factors and fuel consumption values per vehicle kilometre for 276 different traffic situations and different vehicle categories, subdivided by size, type of fuel and emission category, the amount of data is extensive. As HBEFA provides aggregated results for average traffic situations in two aggregation levels, the decision was made to design a model with three levels of detail. For the most detailed version all traffic situations are considered. Those are defined by four parameters: area, street type, speed limit and level of service. Furthermore a number of different road gradients is available. Used in the developed model are four road gradient classes, 0%, ±2%, ±4% and ±6%. The medium level uses aggregated results for highway, rural and urban streets. The most aggregated emission factors are using a German average. For all three levels of aggregation the option of air conditioning for the passenger car is available and cold emission factors per start. Both parameters are included in the model.

The needed electricity consumption values for the electric car are retrieved from the model eLCAr developed in the course of the UMBReLA project, a life cycle assessment of the electric car in comparison to a conventional car. The available values follow the categories of HBEFA which is very convenient. However, only values for the two aggregated levels are available. To be able to match the detailed traffic situations of HBEFA, the fuel consumptions of a reference vehicle was converted to electricity consumption values using conversion factors that were calculated from the eLCAr results.

All emission factors and consumption values were stored in six separate Microsoft Excel data files, forming the database of the developed model.

With the completion of the emission factor and consumption data collection, the construction of the model is approached. As Microsoft Excel was the chosen tool to construct the database, the programming of the model was done in VBA. To make the input of the data easier an input mask was designed that holds the parameter options specific for each model detail. With this input data the corresponding direct emission factors (hot as well as cold start) and consumption values are read from the database. This data is then recalculated from vehicle kilometres to person kilometres and connected with the well-to-tank emission factors. Summing up the hot emissions, cold start emissions and the emissions of the preliminary energy chain (hot and cold start as well) the total CO_2 emissions per person are obtained. In a final step the emissions of all household members are added up. The final results are presented in Microsoft Excel together with the preliminary results.

To provide a tool to collect the mobility data a survey is designed, covering socio-economic data, vehicle data and mobility data via a travel diary. Due to the limitations of the travel diary, the survey is not suitable to collect data as detailed as it would be necessary for the detailed model. GPS tracking would be the better suited method; however, closing the link between the driving profile and the traffic situations of HBEFA could not be covered within this thesis. Reference to pending research on this topic is made.

In order to identify which parameters influence the model outcome most, a sensitivity analysis was carried out using the arc elasticity to describe the influence. Testing all three models, the most important parameters implemented in the model are found to be the direct CO_2 emission factors form HBEFA and, resulting from the direct proportionality, the fuel consumptions. As a consequence the correctness of these values is crucial for the quality of the results. Considering that the values were retrieved from HBEFA, the most commonly used emission factor database in the German-speaking area, the values are considered reliable. As it comes to the electric car, the well-to-tank emission factors are of highest importance.

Of the input parameters, the travel distance and the occupancy rate are identified as the parameters the model is most sensitive to. The next important parameters are the mode of transport and for the detailed model the level of service. All these parameters influence highly the outcome and should thus be investigated in detail when it comes to identifying hotspots of the emission estimation and to suggest measures that have high CO_2 emission saving potential.

To demonstrate how the methodology can be applied, it is used for the sun2car scenario. As, at the time of writing no empirical data was available, a generic dataset was constructed from the MiD database. A baseline scenario for a four-person household covering the mobility data of one day was constructed using German average values for a town size of 20,000 to 50,000 inhabitants. The baseline scenario does not include an electric car. The calculation leads to a total CO_2 emission of 17,505 grams per household per day. A comparison of this result with TREMOD data obtained from MiT showed a good agreement. To assess the effectiveness of different CO_2 reduction measures, the results for different scenarios were calculated. First the electric car is considered in three separate scenarios. As it cannot be foreseen how exactly the introduction of an electric car will influence the mobility behaviour of the household a realistic (electric car is replacing the second car), an optimistic and a pessimistic scenario was constructed. The implementation of the electric car results in a 17% (realistic), a 70% (optimistic) and a 6% (pessimistic) CO_2 emission reduction. The results show that it is crucial how the mobility pattern is changed by the implementation of a measure and that negative changes in the overall mobility behaviour can almost nullify the emission reduction. Further analysis investigated the influence of the parameters that had to be assumed due to the lack of data, namely the occupancy rate and the propulsion technology of the public bus and the electricity composition for the electric car. The effect of changes concerning the public bus was rather insignificant due to the low share of public transportation in the whole mobility scenario. Changes in electricity composition on the other hand showed a moderate effect on the outcome. Additional measures that were tested include a change of occupancy rates and cubic capacities for the private vehicles. Both measures proved to be very effective. Due to its simple realization a change in occupancy rate is considered to be the most efficient.

An evaluation helps to identify the strengths and weaknesses of the presented methodology. The most important weakness is the exclusion of rail transport from the model. While this mode of transport is not needed for the intended application of this thesis, it highly limits the scope of the model. Further limitations are the missing link between driving profile and the detailed traffic situations as input parameters, as well as the simplified approach to retrieve electricity consumption values for the electric car from a reference gasoline vehicle. The latter two points are only concerning the detailed model. From the present point of view, this detailed version of the model can only be used for theoretical analyses treating the electric car values with caution. As for the other two levels of detail the methodology is suitable. Supported with GIS data for the travel distances the methodology is expected to give accurate results. The simple structure and the model being based on commonly used software make the handling easy. The option to choose between different levels of detail ensures the adaptability of the model to different requirements. The fact that the output is already person/household related saves substantial calculating efforts. Thanks to its structure the model can be easily adapted

To conclude, the methodology presented here is suitable for rural to small town context within Germany. Due to the limitations of the travel diary it can only be used for short periods of data collection. Apart from the empirical use it can be utilized for theoretical analyses of CO_2 reduction measures. With the possibility that the identified research gap concerning how to treat the driving profile is closed shortly, the model can be fully used in the foreseeable future.

9.2. Outlook

The aim of this work was to develop a methodology that can be widely used for a CO_2 emission estimation of individual mobility. The resulting model, that can be adapted to different levels of detail according to the specific application, meets these requirements. A test with generic data showed that the model is able to identify CO_2 emission hotspots in the mobility pattern and proved to be a suitable tool to assess the potential of CO_2 reduction measures.

The usefulness of such a tool for political and business decisions in the field of mobility is obvious. The identification of CO_2 emission-intensive trips together with knowledge on the motivation and the restraints of the individual to use the different modes of transport help to design measures that have the potential to change mobility patterns.

However, the question remains which use individual CO_2 emission estimations have for the individual himself/herself. While companies have the public pressure to report on their environmental performance, the individual is not a subject to this burden of proof (Bilharz 2003). Even though the public interest in the environmental effects of individual mobility behaviour is rising the individuals have no strong motive to act upon their individual CO_2 emission estimation. From a theoretical perspective informing the individual is not expected to lead to sustainable effects (Grischkat 2008). How people will respond to their individual CO_2 balance in real life; however, cannot be answered yet. To assess the influence that information on CO_2 emissions can have on individual mobility behaviour, empirical data still has to be awaited. Most promising will be an immediate feedback the probands receive on their smartphones. To make this possible an automation of the data in- and output is indispensable. One of the aims of the sun2car project is to make this possible. The results will show if information on CO_2 emissions is a strong enough argument to break the individual's normal mobility pattern. Even though CO_2 is only one of a wide range of pollutants and GHG, it is by far the most widely known by the public and can thus be expected to have the greatest potential to change the individual's mobility behaviour. It remains to be seen whether individual CO_2 emission estimations have the power to change daily habits.

If the results show that the individual mobility decisions can be influenced by information on CO_2 emissions unknown possibilities are offered. CO_2 emissions could be prevented right at the source of the enormous traffic demand: the individual travel decisions. This would be an important step in the direction of a comprehensive climate change prevention approach. Considering how urgent a reduction of CO_2 emissions is, it becomes clear that technological solutions alone cannot solve the problem. They have to be supplemented by behavioural changes to ensure the target limit for CO_2 declared by the Federal Government is reached in time. Changing daily traveling habits is how every individual can make a contribution, as Ban Ki-moon states: "We have to take ownership […] collectively!" (Ki-moon 2012)

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ANNEX

Annex 1: List of pollutants/components covered by HBEFA

› CO	(carbon monoxide)
› HC	(hydrocarbons [total HC])
› NO_x	(nitrogen oxide)
› PM	(particle matters)
› fuel	(fuel consumption)
› CO_2-total	(= carbon dioxide "total", computed as total CO_2 from fuel consumption; see below)
› CO_2-rep	(= carbon dioxide "reported", i.e. without the biofuel share in the fuel, see below)
› Pb	(lead; see below)
› SO_2	(sulphur dioxide; see below)
› CH_4	(methane, taken from total HC; see below)
› NNHC	(non-methane HC; taken from the total HC; see below)
› Benzene	(taken from total HC; see below)
› Toluene	(taken from total HC; see below)
› Xylene	(taken from total HC; see below)
› N_2O	(nitrous oxide; see below)
› NH_3	(ammonia; see below)

New in HBEFA 3.1 are the following pollutants:

› NO_2	(provided as g/km, but based on %-values of NOx)
› PN	(Partikel number)

(INFRAS 2010)

Annex 2: List of available subsegments in HBEFA

Abbreviations for the vehicle categories

	German	English
2T	2-Takt	2 stroke
3WCat	3-Wege-Katalysator	three-way catalytic converter
4T	4-Takt	4 stroke
AGV82	Schweizer Fahrzeugtyp für leichte Nutzfahrzeuge von 1982	Swiss Vehicle Classification from 1982 for light commercial vehicles
CNG	komprimiertes Erdgas	Compressed natural gas
DPF	Dieselpartikelfilter	Diesel Particulate Filter
ECE	technische Vorschriften für Kraftfahrzeuge der Wirtschaftskommission für Europa	World Forum for Harmonization of Vehicle Regulations
EE	Osteuropäisch	Eastern European
EEV	der gegenwärtig anspruchsvollste europäische Abgasstandard für Busse und Lkw	Enhanced Environmentally Friendly Vehicle
EGR	Abgasrückführung	Exhaust Gas Recirculation
Euro-Norm	europaweite Abgasnorm	european-wide emission standard
Kat/FAV4	RAV4 Katalysator	RAV4 catalytic converter
Kat	Katalysator	catalytic converter
KR	Kraftrad	motorcycle
LPG	Flüssiggas	liquified petroleum gas
SCR	Selektive katalytische Reduktion	selective catalytic reduction
Ucat	ungeregelter Katalysator	unregulated catalytic converter

Vehicle classifications

Passenger car

Gasoline:

3 cubic capacity classes: <1,4L, 1,4-<2L, >=2L

16 Emission standards: Euro-6, Euro-5, Euro-4, Euro-3, Euro-2, Euro-1, ECE-15'04, ECE-15'03, ECE-15'01/02, ECE-15'00, <ECE, PreEuro 3WCat 1987-90, PreEuro 3WCat <1987, AGV82 (CH), Ucat, conv other concepts

Diesel:

3 cubic capacity classes: <1,4L, 1,4-<2L, >=2L

11 Emission standards: Euro-6 DPF, Euro-5 DPF, Euro-4 (DPF)*, Euro-4, Euro-3 (DPF), Euro-3, Euro-2 (DPF), Euro-2, Euro-1, 1986-1988, conv

Natural gas/gasoline mix:

5 emission standards: Euro-6, Euro-5, Euro-4, Euro-3, Euro-2

Liquid gas:

5 emission standards: Euro-6, Euro-5, Euro-4, Euro-3, Euro-2

E85:

Euro-6, Euro-5, Euro-4

*Note: The Diesel Particulate Filter does not have an impact on CO_2 emissions. Both versions are still kept, in case the model should be expanded.

Public bus

Diesel (LBus):

3 tonnage classes: <=15t, 15-18t, >18t

19 emission standards: Euro-VI, Euro-V SCR, Euro-V SCR (DPF), Euro-V EGR, Euro-V EGR (DPF), Euro-IV SCR, Euro-IV SCR (DPF), Euro-IV EGR, Euro-IV EGR (DPF), Euro-III, Euro-III (DPF), Euro-II, Euro-II (DPF), Euro-I, Euro-I (DPF), 80erJahre, 70erJahre, 60erJahre, EE

Natural gas:

3 tonnage classes: <=15t, 15-18t, >18t

1 emission standard: CNG EEV

Motorcycle

Moped:

1 cubic capacity class: <=50cc

10 emission standards: (v<30) EU4, (v<30) EU3, (v<30) EU2, (v<30) mit Kat / FAV4, ohne Kat, Euro-4, Euro-3, Euro-2, Euro-1, preEuro

2 stroke engine (KR 2T):

2 cubic capacity classes: <=150cc, >150cc

6 emission standards: Euro-5, Euro-4, Euro-3, Euro-2, Euro-1, preEuro

4 stroke engine (KR 4T):

4 cubic capacity classes: <=150cc, 151-250cc, 251-750cc, >750cc

6 emission standards: Euro-5, Euro-4, Euro-3, Euro-2, Euro-1, preEuro

Annex 3: Comparison of consumption values for different vehicles

Energy consumption of different vehicles calculated by eLCAr:

	urban	rural	highway
Electric car small [kWh/100km]	17,5	18	22
Electric car medium [kWh/100km]	21	22	27
Electric car large [kWh/100km]	25	24	26,5
Gasoline car small [L/100km]	7	5,5	6
Gasoline car medium [L/100km]	8,5	6,5	7,5
Gasoline car large [L/100km]	12	9	10
Diesel car small [L/100km]	5,5	4,5	5
Diesel car medium [L/100km]	7	5,5	6
Diesel car large [L/100km]	9,5	6,5	7,5

Annex 4: VBA programming codes

Due to space constraints only the code of the main module is shown.

```
Sub getReferenzString(startWeg As Integer, uForm As UserForm, intMode As Integer)

Dim strRef As String
Dim strSpeicherort As String
Dim wkbRef As Workbook
Dim i As Long
Dim j As Long

Dim intColLN As Integer
Dim intColVKS As Integer
Dim intColVKM As Integer
Dim intColMKR As Integer
Dim intColCO2 As Integer
Dim intColKraftStoff As Integer
Dim intColBesetzungsgrad As Integer
Dim intColDistanz As Integer
Dim intColCO2VK As Integer
Dim intColCO2Ges As Integer
Dim intColProPerson As Integer

Dim startRow As Integer

Dim wkbStart As Workbook
Dim wksStart As Worksheet
Dim wksRef As Worksheet

Set wksStart = ActiveSheet
Set wkbStart = ActiveWorkbook

Application.ScreenUpdating = False

' Naming the columns after their content to make the programming clearer
intColLN = 9
intColVKS = 5
intColVKM = 4
intColMKR = 10
intColCO2 = 11
intColKraftStoff = 8
intColBesetzungsgrad = 7
intColDistanz = 6
```

```
intColCO2VK = 2
intColCO2Ges = 3
intColProPerson = 12

'Assigning the according datasheets, that can be found in the same path as the model
If uForm.ComboBox_Fahrzeugtyp.ListIndex = 0 And uForm.CheckBox_Klima = False Then
   strSpeicherort = ThisWorkbook.Path & "\PKW_ohne_Klimaanlage.xlsx"
ElseIf uForm.ComboBox_Fahrzeugtyp.ListIndex = 0 And uForm.CheckBox_Klima = True Then
   strSpeicherort = ThisWorkbook.Path & "\PKW_mit_Klimaanlage.xlsx"
ElseIf uForm.ComboBox_Fahrzeugtyp.ListIndex = 1 Then
   strSpeicherort = ThisWorkbook.Path & "\Elektroauto.xlsx"
ElseIf uForm.ComboBox_Fahrzeugtyp.ListIndex = 2 Then
   strSpeicherort = ThisWorkbook.Path & "\Linienbus.xlsx"
ElseIf uForm.ComboBox_Fahrzeugtyp.ListIndex = 3 Then
   strSpeicherort = ThisWorkbook.Path & "\Motorrad.xlsx"
End If

Set wkbRef = Workbooks.Open(strSpeicherort)
Set wksRef = ActiveSheet

wksStart.Activate

startRow = Range("A:A").Find(CStr("Weg " & startWeg - 1), LookAt:=xlWhole).Row + 1

'Reading out the values from the direct emission datasheets

'simple model (intMode 1):
If intMode = 1 Then
   For i = startRow To Cells(Rows.Count, 5).End(xlUp).Row
      wksStart.Activate
      If Not Cells(i, 4) = "" And Not Left(Cells(i, 1), 3) = "Weg" Then
         strRefVKS = Mid(Cells(i, intColVKS), 2, 100)
         strRefVKM = Cells(i, intColVKM)

'values for the simple model can be found in the sixth worksheet of the corresponding workbook

      wksRef.Activate
      Set wksRef = Worksheets.Item(6)
      wksRef.Activate

'fuel consumption value (mKr)

         For j = 2 To Cells(Rows.Count, 7).End(xlUp).Row
            If Cells(j, 10) = strRefVKM And Cells(j, 5) = "mKr" Then
               wksStart.Cells(i, intColMKR) = wksRef.Cells(j, 19)
            End If
```

```
            Next

'CO2 emission value (CO2 rep.)

            If Not uForm.ComboBox_Fahrzeugtyp.ListIndex = 1 Then
              For j = 2 To Cells(Rows.Count, 7).End(xlUp).Row
                If Cells(j, 10) = strRefVKM And Cells(j, 5) = "CO2(rep.)" Then
                  intLength = Len(Cells(j, 8))
                    wksStart.Cells(i, intColCO2) = wksRef.Cells(j, 19)
                End If
              Next
            End If
          End If
        Next
'medium model (intMode 2):

ElseIf intMode = 2 Then
    For i = startRow To Cells(Rows.Count, 5).End(xlUp).Row
      wksStart.Activate

       If Not Cells(i, 4) = "" Then
         strRefVKS = Cells(i, intColVKS)
         strRefVKM = Cells(i, intColVKM)

'values for the medium model can be found in the fifth worksheet of the corresponding workbook

      wksRef.Activate
      Set wksRef = Worksheets.Item(5)
      wksRef.Activate

'fuel consumption value (mKr)

            For j = 2 To Cells(Rows.Count, 7).End(xlUp).Row
              If Cells(j, 7) = strRefVKS And Cells(j, 10) = strRefVKM And Cells(j, 5) = "mKr" Then
                wksStart.Cells(i, intColMKR) = wksRef.Cells(j, 19)
              End If
            Next

'CO2 emission value (CO2 rep.)

            If Not uForm.ComboBox_Fahrzeugtyp.ListIndex = 1 Then
              For j = 2 To Cells(Rows.Count, 7).End(xlUp).Row
                If Cells(j, 7) = strRefVKS And Cells(j, 10) = strRefVKM And Cells(j, 5) = "CO2(rep.)" Then
                  wksStart.Cells(i, intColCO2) = wksRef.Cells(j, 19)
                End If
              Next
```

```
            End If
        End If
    Next

'detailed model(intMode 3):

ElseIf intMode = 3 Then
    For i = startRow To Cells(Rows.Count, 5).End(xlUp).Row
        wksStart.Activate

         If Not Cells(i, 4) = "" Then
            strRefVKS = Mid(Cells(i, intColVKS), 2, 100)
            strRefVKM = Cells(i, intColVKM)
            strRefLN = Mid(Cells(i, intColLN).Text, Len(Cells(i, intColLN).Text) - 1, 1)



'for the detailed model 4 different road gradients are available, each one in a seperate datasheet (No 1-4)

            wksRef.Activate

            Select Case strRefLN
            Case 0
                Set wksRef = Worksheets.Item(1)
            Case 2
                Set wksRef = Worksheets.Item(2)
            Case 4
                Set wksRef = Worksheets.Item(3)
            Case 6
                Set wksRef = Worksheets.Item(4)
            End Select

            wksRef.Activate

'fuel consumption value (mKr)

            For j = 2 To Cells(Rows.Count, 7).End(xlUp).Row
                If Cells(j, 7) = strRefVKS And Cells(j, 10) = strRefVKM And Cells(j, 5) = "mKr" Then
                    intLength = Len(Cells(j, 8))
                    If Mid(Cells(j, 8), intLength - 1, 1) = strRefLN Then
                        wksStart.Cells(i, intColMKR) = wksRef.Cells(j, 19)
                    End If
                End If
            Next
```

```
'CO2 emission value (CO2 rep.)

         If Not uForm.ComboBox_Fahrzeugtyp.ListIndex = 1 Then
            For j = 2 To Cells(Rows.Count, 7).End(xlUp).Row
               If Cells(j, 7) = strRefVKS And Cells(j, 10) = strRefVKM And Cells(j, 5) = "CO2(rep.)" Then
                  intLength = Len(Cells(j, 8))
                  If Mid(Cells(j, 8), intLength - 1, 1) = strRefLN Then
                     wksStart.Cells(i, intColCO2) = wksRef.Cells(j, 19)
                  End If
               End If
            Next
         End If
      End If
   Next
End If

'Implementing the well-to-tank emission values [g CO2/g fuel], in the case of electricity: [g CO2 /kWh]

Dim dblRefValue As Double
wksStart.Activate
For i = startRow To Cells(Rows.Count, intColKraftStoff).End(xlUp).Row
   If Not Cells(i, intColVKM) = "" Then
      If Cells(i, intColKraftStoff).Text = "Benzin" Then
         dblRefValue = 0.599047152
      ElseIf Cells(i, intColKraftStoff).Text = "Diesel" Then
         dblRefValue = 0.452369484
      ElseIf Cells(i, intColKraftStoff).Text = "E85" Then
         dblRefValue = 0.677731007
      ElseIf Cells(i, intColKraftStoff).Text = "Erdgas" Then
         dblRefValue = 0.321609574
      ElseIf Cells(i, intColKraftStoff).Text = "Erdgas/Benzin Gemisch" Then
         dblRefValue = 0.460328363
      ElseIf Cells(i, intColKraftStoff).Text = "Flüssiggas" Then
         dblRefValue = 0.315924454726044
      ElseIf Cells(i, intColKraftStoff).Text = "Strom (Mix Deutschland)" Then
         dblRefValue = 540.712756742979
      ElseIf Cells(i, intColKraftStoff).Text = "Strom (PV)" Then
         dblRefValue = 92.3219926142406
      ElseIf Cells(i, intColKraftStoff).Text = "Strom (50% Mix, 50% PV)" Then
         dblRefValue = 316.5173747
      ElseIf Cells(i, intColKraftStoff).Text = "Strom (25% Mix, 75% PV)" Then
         dblRefValue = 204.4196836
      ElseIf Cells(i, intColKraftStoff).Text = "Strom (75% Mix, 25% PV)" Then
         dblRefValue = 428.6150657
      End If
```

```
'CO2 Emissions_well-to-tank [g CO2 / vehicle]= Fuel consumption*Distance*CO2 Emission factor_well-to-tank

      Cells(i, intColCO2VK) = Cells(i, intColMKR).Value * Cells(i, intColDistanz).Value * dblRefValue

'CO2 Emissions_total [g CO2 / vehicle] = CO2 Emissions_well-to-tank + direct CO2 Emissions*Distance

    Cells(i, intColCO2Ges) = Cells(i, intColCO2VK).Value + Cells(i, intColCO2).Value * Cells(i,
intColDistanz).Value

    If Left(Cells(i, intColVKM), 3) = "LBu" Then
      Cells(i, intColProPerson) = Cells(i, intColCO2Ges) / (Cells(i, intColBesetzungsgrad).Value * 100)
    ElseIf Left(Cells(i, intColVKM), 3) = "PKW" Then
      Cells(i, intColProPerson) = Cells(i, intColCO2Ges) / (Cells(i, intColBesetzungsgrad).Value * 5)
    ElseIf Left(Cells(i, intColVKM), 3) = "Ele" Then
      Cells(i, intColProPerson) = Cells(i, intColCO2Ges) / (Cells(i, intColBesetzungsgrad).Value * 5)
    Else
      Cells(i, intColProPerson) = Cells(i, intColCO2Ges) / (Cells(i, intColBesetzungsgrad).Value * 2)
    End If
  End If
Next

Application.DisplayAlerts = False
wkbRef.Close
Application.DisplayAlerts = True

Application.ScreenUpdating = True

End Sub
```

```
Sub calcSums(strRef As String, Optional intCalcMode As Integer = 1)

'calculation of the cold start emissions --> only for the passeneger car

If intCalcMode = 2 Then
  intColKraftStoff = 8
  intColVKM = 4
  For j = 5 To Cells(Rows.Count, intColKraftStoff).End(xlUp).Row
    If Not Cells(j, intColVKM) = "" Then
      If Cells(j, intColKraftStoff).Text = "Benzin" Then
        dblRefValue = 0.599047152
      ElseIf Cells(j, intColKraftStoff).Text = "Diesel" Then
        dblRefValue = 0.452369484
      ElseIf Cells(j, intColKraftStoff).Text = "E85" Then
        dblRefValue = 0.677731007
      ElseIf Cells(j, intColKraftStoff).Text = "Erdgas" Then
        dblRefValue = 0.321609574
```

```
        ElseIf Cells(j, intColKraftStoff).Text = "Erdgas/Benzin Gemisch" Then
          dblRefValue = 0.460328363
        ElseIf Cells(j, intColKraftStoff).Text = "Flüssiggas" Then
          dblRefValue = 0.315924454726044
        End If

        'CO2 cold start emissions_well-to-tank = cold start fuel consumption*CO2 emission factor_well-to-tank

        Cells(j, 13) = Cells(j, 13).Value * dblRefValue
      End If
    Next
End If

' Formatting of household member work sheet and overview --> sums in blue

For i = 4 To Cells(Rows.Count, 1).End(xlUp).Row + 1
    intStrLength = Len(strRef)
    If Left(Cells(i, 1), intStrLength) = strRef Then
      startRow = i + 1
      If intCalcMode = 1 Then
        Range(Cells(i, 1), Cells(i, 12)).Interior.Color = RGB(31, 73, 125)
        Range(Cells(i, 1), Cells(i, 12)).Font.Color = RGB(255, 255, 255)
      ElseIf intCalcMode = 2 Then
        Range(Cells(i, 1), Cells(i, 14)).Interior.Color = RGB(31, 73, 125)
        Range(Cells(i, 1), Cells(i, 14)).Font.Color = RGB(255, 255, 255)
      End If
    End If

    If Cells(i, 1) = "" Then
      EndRow = i
  'summing up the trip subsection values in the household member sheet

  If intCalcMode = 1 Then
  Range(Cells(startRow - 1, 2), Cells(startRow - 1, 12)).ClearContents
  Cells(startRow - 1, 2) = Application.WorksheetFunction.Sum(Range(Cells(startRow, 2), Cells(EndRow - 1, 2)))
  Cells(startRow - 1, 3) = Application.WorksheetFunction.Sum(Range(Cells(startRow, 3), Cells(EndRow - 1, 3)))
  Cells(startRow - 1, 4) = Cells(startRow, 4)
  Cells(startRow - 1, 6) = Application.WorksheetFunction.Sum(Range(Cells(startRow, 6), Cells(EndRow - 1, 6)))
  Cells(startRow - 1, 8) = Cells(startRow, 8)
  Cells(startRow - 1, 10) = Application.WorksheetFunction.Sum(Range(Cells(startRow, 10), Cells(EndRow - 1, 10)))
  Cells(startRow - 1, 11) = Application.WorksheetFunction.Sum(Range(Cells(startRow, 11), Cells(EndRow - 1, 11)))
  Cells(startRow - 1, 12) = Application.WorksheetFunction.Sum(Range(Cells(startRow, 12), Cells(EndRow - 1, 12)))
   For k = startRow To EndRow - 1
       Cells(startRow - 1, 7) = Cells(startRow - 1, 7) + Cells(k, 7) * Cells(k, 6)
   Next
   Cells(startRow - 1, 7) = Cells(startRow - 1, 7) / Cells(startRow - 1, 6)
```

```
'summing up the trips per household member in the overview sheet

      ElseIf intCalcMode = 2 Then
        Cells(startRow - 1, 6) = Application.WorksheetFunction.Sum(Range(Cells(startRow, 6), Cells(EndRow - 1, 6)))
          For k = startRow To EndRow - 1
            Cells(startRow - 1, 7) = Cells(startRow - 1, 7) + Cells(k, 7) * Cells(k, 6)
            Cells(k, 13) = Cells(k, 13) / (Cells(k, 7) * 5)
            Cells(k, 14) = Cells(k, 14) / (Cells(k, 7) * 5)
            Cells(k, 12) = Cells(k, 12) + Cells(k, 13) + Cells(k, 14)
          Next
          On Error Resume Next
  Cells(startRow - 1, 7) = Cells(startRow - 1, 7) / Cells(startRow - 1, 6)
  Cells(startRow - 1, 10) = Application.WorksheetFunction.Sum(Range(Cells(startRow, 10), Cells(EndRow - 1, 10)))
  Cells(startRow - 1, 11) = Application.WorksheetFunction.Sum(Range(Cells(startRow, 11), Cells(EndRow - 1, 11)))
  Cells(startRow - 1, 12) = Application.WorksheetFunction.Sum(Range(Cells(startRow, 12), Cells(EndRow - 1, 12)))
  Cells(startRow - 1, 14) = Application.WorksheetFunction.Sum(Range(Cells(startRow, 14), Cells(EndRow - 1, 14)))
  Cells(startRow - 1, 13) = Application.WorksheetFunction.Sum(Range(Cells(startRow, 13), Cells(EndRow - 1, 13)))
  Cells(startRow - 1, 2) = Application.WorksheetFunction.Sum(Range(Cells(startRow, 2), Cells(EndRow - 1, 2)))
  Cells(startRow - 1, 3) = Application.WorksheetFunction.Sum(Range(Cells(startRow, 3), Cells(EndRow - 1, 3)))

'If no trip is chosen --> "No trip has been chosen for this household member." appears in the overview
          If Err Then
            Cells(startRow - 1, 12) = "Für dieses Haushaltsmitglied wurde kein Weg ausgewählt!"
            Err.Clear
          End If
        End If
    End If
Next

End Sub
```

```
'Overview

Sub addÜbersicht()

Application.ScreenUpdating = False

Dim wkbStart As Workbook
Dim wksÜbersicht As Worksheet
Dim wksRef As Worksheet
Dim intCounter As Integer

Set wkbStart = ActiveWorkbook
```

```
intCounter = wkbStart.Worksheets.Count

For i = 1 To intCounter
   Set wksTemp = Worksheets.Item(i)
   If wksTemp.Name = "Übersicht" Then
      Application.DisplayAlerts = False
         wksTemp.Delete
      Application.DisplayAlerts = True
      Exit For
   End If
Next

Set wksÜbersicht = wkbStart.Worksheets.Add(Before:=wkbStart.Worksheets.Item(1))
wksÜbersicht.Name = "Übersicht"

'Insert heading + formatting

Cells(1, 1) = "CO2 Emissionen Gesamtübersicht "
Cells(1, 12) = "inklusive Kaltstartemissionen"
Cells(1, 1).Font.Size = 12
Cells(1, 1).Font.Bold = True
Cells(1, 12).Font.Size = 12
Cells(1, 12).Font.Bold = True
Cells(2, 1) = "Summe Haushalt"
Cells(2, 1).Font.Size = 11
Cells(2, 1).Interior.Color = RGB(255, 255, 171)
Cells(2, 12).Interior.Color = RGB(255, 255, 171)
Cells(2, 4) = "[g CO2/Haushalt]"
Cells(2, 4).Font.Size = 11
Cells(2, 4).Interior.Color = RGB(255, 255, 171)

'Copy column headings from the household member sheet

k = 5
Set wksRef = wkbStart.Worksheets.Item(2)
wksRef.Activate
Range(Cells(3, 1), Cells(3, 12)).Copy Destination:=wksÜbersicht.Cells(k - 2, 1)

'Insert additional columns for cold start emissions

wksÜbersicht.Activate
Cells(3, 13) = "Kaltstart Emissionen Vorkette [g CO2/Start und Person]"
Cells(3, 13).Interior.Color = RGB(255, 255, 171)
Cells(3, 14) = "Kaltstart Emissionen direkt[g CO2/Start und Person]"
Cells(3, 14).Interior.Color = RGB(255, 255, 171)
```

```
intCounter = wkbStart.Worksheets.Count
For i = 2 To intCounter
   Set wksRef = wkbStart.Worksheets.Item(i)
   wksRef.Activate
   Call calcSums("Weg", 1)
   wksÜbersicht.Cells(k - 1, 1) = wksRef.Name
   For j = 4 To Cells(Rows.Count, 1).End(xlUp).Row + 1
      If Left(Cells(j, 1), 3) = "Weg" Then
         Range(Cells(j, 1), Cells(j, 12)).Copy Destination:=wksÜbersicht.Cells(k, 1)
         k = k + 1
      End If
   Next
   k = k + 2
Next

wksÜbersicht.Columns.AutoFit
wksÜbersicht.Activate
Range(Cells(4, 1), Cells(Cells(Rows.Count, 1).End(xlUp).Row, Cells(3, Columns.Count).End(xlToLeft).Column)).ClearFormats

' Cold start emission values are readout form the "coldstart_passenger car" file

intColVKM = 4

Set wkbRef = Workbooks.Open(ThisWorkbook.Path & "\Kaltstart_Pkw.xlsx")
Set wksRef = ActiveSheet
wksÜbersicht.Activate

For i = 5 To Cells(Rows.Count, 4).End(xlUp).Row
   wksÜbersicht.Activate
   If Cells(i, 4) <> "" And Left(Cells(i, 4), 3) = "PKW" Then
      strRefVKM = Cells(i, intColVKM)
   wksRef.Activate
      For j = 2 To Cells(Rows.Count, 7).End(xlUp).Row
         If Cells(j, 9) = strRefVKM And Cells(j, 5) = "mKr" Then
            wksÜbersicht.Cells(i, 13) = wksRef.Cells(j, 15)
         End If
      Next
      For j = 2 To Cells(Rows.Count, 7).End(xlUp).Row
         If Cells(j, 9) = strRefVKM And Cells(j, 5) = "CO2(rep.)" Then
            wksÜbersicht.Cells(i, 14) = wksRef.Cells(j, 15)
         End If
      Next
   End If
Next
```

```
Application.DisplayAlerts = False
wkbRef.Close
Application.DisplayAlerts = True

calcSums "Haushaltsmitglied", 2

'Shifting the columns

Cells(1, 12).EntireColumn.Cut
Cells(1, 2).EntireColumn.Insert Shift:=xlToRight

Cells(1, 3).EntireColumn.Cut
Cells(1, 15).EntireColumn.Insert Shift:=xlToRight

Cells(1, 3).EntireColumn.Cut
Cells(1, 15).EntireColumn.Insert Shift:=xlToRight

'Delete column on traffic situation and road gradient in the overview since there are different ones within one trip -->
no summing up possible

wksÜbersicht.Activate
Cells(1, 8).EntireColumn.Delete
Cells(1, 4).EntireColumn.Delete


Cells(2, 2) = 0

For i = 4 To Cells(Rows.Count, 2).End(xlUp).Row
   If Cells(i, 2).Interior.Color = RGB(31, 73, 125) Then
      Cells(2, 2) = Cells(2, 2) + Cells(i, 2)
   End If
Next

setColumnFormats 5, FormatMode:=3

'Add Reset button

ActiveSheet.Buttons.Add(525, 1.5, 138.75, 27.75).Select
Selection.Caption = "Neustart"
Selection.OnAction = "Neustart"
Cells(1, 1).Activate
End Sub
```

```
' add a new household member worksheet with the same properties as the worksheet "Household member_1"

Sub addFamMit(uForm As UserForm)
```

```
Dim wkbStart As Workbook
Dim wksStart As Worksheet
Dim wksRef As Worksheet
Dim wksTemp As Worksheet

Set wksStart = ActiveSheet
Set wkbStart = ActiveWorkbook

Unload uForm
For i = 1 To wkbStart.Worksheets.Count
   Set wksTemp = Worksheets.Item(i)
   If wksTemp.Name = "Übersicht" Then
      Application.DisplayAlerts = False
         wksTemp.Delete
      Application.DisplayAlerts = True
      Exit For
   End If
Next

wkbStart.Worksheets(1).Copy after:=wkbStart.Worksheets(Worksheets.Count)
Set wksTemp = wkbStart.Worksheets(Worksheets.Count)
wksTemp.Name = "Haushaltsmitglied_" & wkbStart.Worksheets.Count
wksTemp.Activate
Range(Cells(4, 1), Cells(Cells(Rows.Count, 1).End(xlUp).Row, 1)).EntireRow.Delete
Cells(1, 1) = "CO2 Emissionen " & wksTemp.Name & " ohne Kaltstartemissionen"
Cells(1, 1).Font.Size = 12
Cells(1, 1).Font.Bold = True

End Sub
```

```
'What happens when the Reset button is pressed --> file is saved in the same folder as the model \Desktop\CO2 Modell
'Whole workbook is reset to how it was in the beginning (only household member 1)

Sub Neustart()

On Error GoTo handler
strSave = Environ$("Userprofile") & "\Desktop\CO2 Model\Haushalt_"
strName = Application.GetSaveAsFilename(strSave, "Excel-Dateien mit Makros (*.xlsm),*.xls")

ActiveWorkbook.SaveCopyAs Filename:=strName

Dim wkbTemp As Workbook
Set wkbTemp = ActiveWorkbook
```

```
intCounter = wkbTemp.Worksheets.Count
For i = intCounter To 1 Step -1
   Set wksTemp = Worksheets.Item(i)
   If wksTemp.Name <> "Haushaltsmitglied_1" Then
      Application.DisplayAlerts = False
         wksTemp.Delete
      Application.DisplayAlerts = True
   End If
Next

Set wksTemp = ActiveSheet
Dim clearRange As Range
Set clearRange = wksTemp.Range("A4:GG100")
clearRange.ClearFormats
clearRange.ClearContents

Exit Sub

handler:
MsgBox "Die Datei konnte nicht unter diesem Namen gespeichert werden, bitte wiederholen!"
End Sub
```

```
'New trip/subsection of the trip is added

Sub addWeg(counter As Integer, uForm As UserForm, intMode As Integer)

Dim strWeg As String
Dim intInsertRow As String
Dim intCounterTs As Integer
Dim strCB As String
Dim contS1 As Control
Dim i As Integer
Dim wksA As Worksheet

Set wksA = ActiveSheet

If uForm.OptionButton_TS1 = True Then
   intCounterTs = 1
ElseIf uForm.OptionButton_TS2 = True Then
   intCounterTs = 2
ElseIf uForm.OptionButton_TS3 = True Then
   intCounterTs = 3
ElseIf uForm.OptionButton_TS4 = True Then
   intCounterTs = 4
ElseIf uForm.OptionButton_TS5 = True Then
   intCounterTs = 5
```

```
End If

With wksA
   intInsertRow = Cells(Rows.Count, 1).End(xlUp).Row
   If intInsertRow < 4 Then
      intInsertRow = 4
   Else
      intInsertRow = intInsertRow + 2
   End If

'New trip is added one line below the last trip

   .Cells(intInsertRow, 1) = uForm.strWeg
   For i = 1 To intCounterTs

'String for the subsection is composed

      .Cells(intInsertRow + i, 1) = "Teilstrecke " & Right(uForm.strWeg.Caption, 1) & "." & i
   Next

'The chosen parameters from the user form are inserted into the active worksheet

   For i = 1 To intCounterTs
      For Each contS1 In uForm.Controls
         If TypeName(contS1) = "TextBox" And Right(contS1.Name, 1) = i Then
            .Cells(intInsertRow + i, 6) = contS1.Value
         End If
      Next
   Next

   For i = 1 To intCounterTs
      For Each contS1 In uForm.Controls
         If TypeName(contS1) = "ComboBox" And Right(contS1.Name, 1) = i And Left(contS1.Name, 11) =
"ComboBox_BG" Then
            .Cells(intInsertRow + i, 7) = contS1.Value
         End If
      Next
   Next

'For the different model some parameters vary

'simple Model
'Traffic situation and road gradient are German averages

   If intMode = 1 Then
      For i = 1 To intCounterTs
```

```
      .Cells(intInsertRow + i, 5) = "Ø Deutschland"
    Next

    For i = 1 To intCounterTs
      .Cells(intInsertRow + i, 9) = "Ø Deutschland"
    Next

'medium Model
'road gradient is a German average, traffic situation is readout

  ElseIf intMode = 2 Then
    For i = 1 To intCounterTs
      For Each contS1 In uForm.Controls
        If TypeName(contS1) = "ComboBox" And Right(contS1.Name, 1) = i And Not Left(contS1.Name, 11) =
"ComboBox_BG" And Not Left(contS1.Name, 11) = "ComboBox_LN" Then
          .Cells(intInsertRow + i, 5) = .Cells(intInsertRow + i, 5) & contS1.Value
        End If
      Next
    Next
    For i = 1 To intCounterTs
      .Cells(intInsertRow + i, 9) = "Ø Deutschland"
    Next

'detailed Model
'road gradient and traffic situation are readout

  ElseIf intMode = 3 Then
    For i = 1 To intCounterTs
      For Each contS1 In uForm.Controls
        If TypeName(contS1) = "ComboBox" And Right(contS1.Name, 1) = i And Not Left(contS1.Name, 11) =
"ComboBox_BG" And Not Left(contS1.Name, 11) = "ComboBox_LN" Then
          .Cells(intInsertRow + i, 5) = .Cells(intInsertRow + i, 5) & "/" & contS1.Value
        End If
      Next
    Next
    For i = 1 To intCounterTs
      For Each contS1 In uForm.Controls
        If TypeName(contS1) = "ComboBox" And Right(contS1.Name, 1) = i And Left(contS1.Name, 11) =
"ComboBox_LN" Then
          .Cells(intInsertRow + i, 9) = contS1.Text
        End If
      Next
    Next
  End If
    For i = 1 To intCounterTs
      .Cells(intInsertRow + i, 4) = uForm.ComboBox_Subsegment.Text
```

```
    Next
    For i = 1 To intCounterTs
      .Cells(intInsertRow + i, 8) = uForm.ComboBox_KsTyp.Text
    Next

End With

'Trip Number is changed in the user form

setColumnFormats 7, FormatMode:=3

strWeg = "Weg " & counter
uForm.strWeg = strWeg
End Sub
```

```
Sub einfacheFormAnzeigen()

EditFormData.ClearFormates_DeleteUebersicht
Form_Selection_einfach.Show
End Sub
```

```
Sub LoadForm()
uForm.Show
End Sub
```

```
Sub unloadform()

Unload Me
End Sub
```

```
'Different formats for the columns are set

Sub setColumnFormats(intCol As Integer, Optional wksIn As Worksheet, Optional FormatMode As Integer = 1)

Dim rngCol As Range
Dim wksA As Worksheet

Dim i As Long

If wksIn Is Nothing Then
  Set wksA = ActiveSheet
Else
  Set wksA = wksIn
End If

With wksA
```

```
  Set rngCol = .Cells(1, intCol)
    With rngCol
      rngCol.EntireColumn.NumberFormat = "General"
      rngCol.EntireColumn.TextToColumns DataType:=xlDelimited, _
          TextQualifier:=xlDoubleQuote, ConsecutiveDelimiter:=False, Tab:=False, _
          Semicolon:=False, Comma:=False, Space:=False, Other:=False, OtherChar _
          :=False, FieldInfo:=Array(1, 1), TrailingMinusNumbers:=True, DecimalSeparator:="Comma"
      .EntireColumn.Replace "#*", "Fehler", LookAt:=xlWhole
      .EntireColumn.Replace "=", "", LookAt:=xlPart
    End With

  Select Case FormatMode
    Case 1
    rngCol.EntireColumn.NumberFormat = "General"

    Case 2
    rngCol.EntireColumn.NumberFormat = "dd.mm.yyyy"

    Case 3
    rngCol.EntireColumn.NumberFormat = "0.00%"

    Case 4
    rngCol.EntireColumn.NumberFormat = "0.00€"
  End Select
End With
End Sub
```

Annex 5: Manual for the model

1. Save all the files in one folder. Preferably the folder is called “CO2 Modell” and is saved on the Desktop. In this case the calculated results are automatically saved in the same folder. If another path is preferred the code has to be adapted:
   - ➔ VBA module “main” (press Alt+F11) to open the VBA project
   - ➔ “Sub Neustart()”
   - ➔ strSave = Environ$("Userprofile") & "\Desktop\CO2 Modell\Haushalt_"
2. Open file “CO2 Modell”
3. Enable macros, if necessary.
4. Press “Start”
5. Fill in the data for the first trip of the first household member
6. Press “Weg einfügen” to assign the data for the first trip
7. Repeat step 4 to 5 for all trips of the first household member
8. Press “Haushaltsmitglied hinzufügen” to add a new household member
9. Repeat step 4 to 7 for each household member
10. When all data is filled in: press “Übersicht erstellen” to calculate the results
11. To start a new calculation press “Neustart” in the “Übersicht” tab
12. Save file under a new name (“Haushalt_X”), the preset data storage path will be the created folder “CO2 Modell”

Note: If the input has to be adapted, it is not necessary to run the whole input process again. It is enough to open the respective household member sheet, to delete the erroneous cells, press “Start” to fill in the new data and to calculate the new results with “Übersicht erstellen”.

Annex 6: Survey documents

Household and vehicle data

MUSTER

EvaSys	Erfassung der Haushalts- und Fahrzeugdaten	Electric Paper

Markieren Sie so: ☐ ☒ ☐ ☐ ☐ Bitte verwenden Sie einen Kugelschreiber oder nicht zu starken Filzstift. Dieser Fragebogen wird maschinell erfasst.

Korrektur: ☐ ■ ☐ ☒ ☐ Bitte beachten Sie im Interesse einer optimalen Datenerfassung die links gegebenen Hinweise beim Ausfüllen.

1. Sozioökonomische Daten

1.1 Name:

1.2 Geschlecht:
- ☐ männlich
- ☐ weiblich

1.3 Alter:

1.4 Berufstätigkeit:
- ☐ Vollzeit
- ☐ Teilzeit
- ☐ Auszubildende(r)
- ☐ nicht berufstätig

1.5 Ihre gegenwärtige Tätigkeit, wenn nicht berufstätig:
- ☐ Schüler(in)
- ☐ Student(in)
- ☐ zur Zeit arbeitslos
- ☐ vorübergehend freigestellt
- ☐ Hausfrau/-mann
- ☐ Rentner(in), Pensionär(in)
- ☐ Bundesfreiwilligendienstleistender
- ☐ anderes

1.6 Führerscheinbesitz für Pkw:
- ☐ Ja
- ☐ Nein

1.7 Wie hoch ist das monatliche Nettoeinkommen Ihres Haushalts in Euro ungefähr?
- ☐ bis unter 500 Euro pro Monat
- ☐ 500 bis unter 900 Euro pro Monat
- ☐ 900 bis unter 1.500 Euro pro Monat
- ☐ 1.500 bis unter 2.000 Euro pro Monat
- ☐ 2.000 bis unter 2.500 Euro pro Monat
- ☐ 2.500 bis unter 3.000 Euro pro Monat
- ☐ 3.000 bis unter 3.500 Euro pro Monat
- ☐ 3.500 bis unter 4.000 Euro pro Monat
- ☐ 4.000 bis unter 4.500 Euro pro Monat
- ☐ 4.500 bis unter 5.000 Euro pro Monat
- ☐ 5.000 bis unter 5.500 Euro pro Monat
- ☐ 5.500 bis unter 6.000 Euro pro Monat
- ☐ 6.000 bis unter 6.500 Euro pro Monat
- ☐ 6.500 bis unter 7.000 Euro pro Monat
- ☐ mehr als 7.000 Euro pro Monat

MUSTER

MUSTER

EvaSys	Erfassung der Haushalts- und Fahrzeugdaten	Electric Paper

2. Fahrzeugdaten

Auto 1

2.1 Hersteller:

2.2 Typ / Modell:

2.3 Baujahr / Erstzulassung:

2.4 Antriebsart:

☐ Benzin ☐ Diesel ☐ Erdgas/Benzin-Gemisch
☐ Flüssiggas ☐ E85 ☐ Elektroantrieb

Auto 2

2.5 Hersteller:

2.6 Typ / Modell:

2.7 Baujahr / Erstzulassung:

2.8 Antriebsart:

☐ Benzin ☐ Diesel ☐ Erdgas/Benzin-Gemisch
☐ Flüssiggas ☐ E85 ☐ Elektroantrieb

Auto 3

2.9 Hersteller:

2.10 Typ / Modell:

2.11 Baujahr / Erstzulassung:

2.12 Antriebsart:

☐ Benzin ☐ Diesel ☐ Erdgas/Benzin-Gemisch
☐ Flüssiggas ☐ E85 ☐ Elektroantrieb

MUSTER

EvaSys	Erfassung der Haushalts- und Fahrzeugdaten	Electric Paper

3. Fahrzeugdaten

Motorrad 1

3.1 Hersteller:

3.2 Typ / Modell:

3.3 Baujahr / Erstzulassung:

Motorrad 2

3.4 Hersteller:

3.5 Typ / Modell:

3.6 Baujahr / Erstzulassung:

Motorrad 3

3.7 Hersteller:

3.8 Typ / Modell:

3.9 Baujahr / Erstzulassung:

MUSTER

Vehicle data public transportation

MUSTER

EvaSys	Fragebogen Fahrzeugdaten Bus	Electric Paper

Markieren Sie so: ☐ ☒ ☐ ☐ ☐ Bitte verwenden Sie einen Kugelschreiber oder nicht zu starken Filzstift. Dieser Fragebogen wird maschinell erfasst.

Korrektur: ☐ ■ ☐ ☒ ☐ Bitte beachten Sie im Interesse einer optimalen Datenerfassung die links gegebenen Hinweise beim Ausfüllen.

1. Allgemeine Fragen

1.1 Wie viele Busse sind im Einsatz?

1.2 Wie viele verschiedene Modelle sind im Einsatz?

1.3 Falls Sie Informationen dazu haben, was sind die durchschnittlichen Auslastungsgrade Ihrer Busse (zu Stoßzeiten und außerhalb der Stoßzeiten)?

2. Fahrzeugdaten

Fahrzeugtyp 1

2.1 Hersteller:

2.2 Typ / Modell:

2.3 Baujahr / Erstzulassung:

2.4 Antriebsart:
☐ Diesel ☐ Erdgas

2.5 Anzahl der vorhandenen Fahrzeuge dieser Art:

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MUSTER

EvaSys	Fragebogen Fahrzeugdaten Bus	Electric Paper

2. Fahrzeugdaten [Fortsetzung]

Fahrzeugtyp 2

2.6 Hersteller:

2.7 Typ / Modell:

2.8 Baujahr / Erstzulassung:

2.9 Antriebsart:
☐ Diesel ☐ Erdgas

2.10 Anzahl der vorhandenen Fahrzeuge dieser Art:

Fahrzeugtyp 3

2.11 Hersteller:

2.12 Typ / Modell:

2.13 Baujahr / Erstzulassung:

2.14 Antriebsart:
☐ Diesel ☐ Erdgas

2.15 Anzahl der vorhandenen Fahrzeuge dieser Art:

MUSTER

Travel diary

Simple version

1. Weg
Datum: ____________
Uhrzeit Abfahrt: ____________
Abfahrtsort falls nicht Heimtadresse: ______________________________ ______________________________
Verkehrsmittel: Pkw als Fahrer ☐ Pkw als Mitfahrer ☐ Elektroauto als Fahrer ☐ Elektroauto als Mitfahrer ☐ Motorrad als Fahrer ☐ Motorrad als Mitfahrer ☐ Bus ☐ Fahrrad ☐ Zu Fuß ☐ Anderes, und zwar: ____________
Falls das gewählte Verkehrsmittel ein eigenes Fahrzeug ist: Welches Modell? ____________
Uhrzeit Ankunft: ____________
Adresse Ankunftsort: ______________________________ ______________________________
Anzahl der Mitreisenden: ______ oder Besetzungsgrad des ÖPNV: ______ %

Für jeden neuen Weg nutzen Sie bitte die nächste Spalte. Der Endpunkt des letzten Weges ist der Anfangspunkt des nächsten.

2. Weg
Datum: ____________
Uhrzeit Abfahrt: ____________
Verkehrsmittel: Pkw als Fahrer ☐ Pkw als Mitfahrer ☐ Elektroauto als Fahrer ☐ Elektroauto als Mitfahrer ☐ Motorrad als Fahrer ☐ Motorrad als Mitfahrer ☐ Bus ☐ Fahrrad ☐ Zu Fuß ☐ Anderes, und zwar: ____________
Falls das gewählte Verkehrsmittel ein eigenes Fahrzeug ist: Welches Modell? ____________
Uhrzeit Ankunft: ____________
Adresse Ankunftsort: ______________________________ ______________________________
Anzahl der Mitreisenden: ______ oder Besetzungsgrad des ÖPNV: ______ %

Für jeden neuen Weg nutzen Sie bitte die nächste Spalte. Der Endpunkt des letzten Weges ist der Anfangspunkt des nächsten.

3. Weg	
Datum:	________
Uhrzeit Abfahrt:	________
Verkehrsmittel:	
Pkw als Fahrer	☐
Pkw als Mitfahrer	☐
Elektroauto als Fahrer	☐
Elektroauto als Mitfahrer	☐
Motorrad als Fahrer	☐
Motorrad als Mitfahrer	☐
Bus	☐
Fahrrad	☐
Zu Fuß	☐
Anderes, und zwar:	________
Falls das gewählte Verkehrsmittel ein eigenes Fahrzeug ist: Welches Modell?	________
Uhrzeit Ankunft:	________
Adresse Ankunftsort: ________ ________	
Anzahl der Mitreisenden:	______
oder	
Besetzungsgrad des ÖPNV:	______ %

4. Weg	
Datum:	________
Uhrzeit Abfahrt:	________
Verkehrsmittel:	
Pkw als Fahrer	☐
Pkw als Mitfahrer	☐
Elektroauto als Fahrer	☐
Elektroauto als Mitfahrer	☐
Motorrad als Fahrer	☐
Motorrad als Mitfahrer	☐
Bus	☐
Fahrrad	☐
Zu Fuß	☐
Anderes, und zwar:	________
Falls das gewählte Verkehrsmittel ein eigenes Fahrzeug ist: Welches Modell?	________
Uhrzeit Ankunft:	________
Adresse Ankunftsort: ________ ________	
Anzahl der Mitreisenden:	______
oder	
Besetzungsgrad des ÖPNV:	______ %

Für jeden neuen Weg nutzen Sie bitte die nächste Spalte. Der Endpunkt des letzten Weges ist der Anfangspunkt des nächsten.

Für jeden neuen Weg nutzen Sie bitte die nächste Spalte. Der Endpunkt des letzten Weges ist der Anfangspunkt des nächsten.

Medium version

1. Weg
Datum: __________
Uhrzeit Abfahrt: __________
Abfahrtsort falls nicht Heimtadresse: ____________________
Verkehrsmittel: Pkw als Fahrer ☐ Pkw als Mitfahrer ☐ Elektroauto als Fahrer ☐ Elektroauto als Mitfahrer ☐ Motorrad als Fahrer ☐ Motorrad als Mitfahrer ☐ Bus ☐ Fahrrad ☐ Zu Fuß ☐ Anderes, und zwar: __________
Falls das gewählte Verkehrsmittel ein eigenes Fahrzeug ist: Welches Modell? __________
Uhrzeit Ankunft: __________
Adresse Ankunftsort: ____________________
Anzahl der Mitreisenden: _____ oder Besetzungsgrad des ÖPNV: _____ %
Wieviel Prozent des Weges waren Sie auf folgenden Straßentypen unterwegs? Innerorts: __________ % Außerorts: __________ % Autobahn: __________ %

2. Weg
Datum: __________
Uhrzeit Abfahrt: __________
Verkehrsmittel: Pkw als Fahrer ☐ Pkw als Mitfahrer ☐ Elektroauto als Fahrer ☐ Elektroauto als Mitfahrer ☐ Motorrad als Fahrer ☐ Motorrad als Mitfahrer ☐ Bus ☐ Fahrrad ☐ Zu Fuß ☐ Anderes, und zwar: __________
Falls das gewählte Verkehrsmittel ein eigenes Fahrzeug ist: Welches Modell? __________
Uhrzeit Ankunft: __________
Adresse Ankunftsort: ____________________
Anzahl der Mitreisenden: _____ oder Besetzungsgrad des ÖPNV: _____ %
Wieviel Prozent des Weges waren Sie auf folgenden Straßentypen unterwegs? Innerorts: __________ % Außerorts: __________ % Autobahn: __________ %

Für jeden neuen Weg nutzen Sie bitte die nächste Spalte. Der Endpunkt des letzten Weges ist der Anfangspunkt des nächsten.

Für jeden neuen Weg nutzen Sie bitte die nächste Spalte. Der Endpunkt des letzten Weges ist der Anfangspunkt des nächsten.

Annex 7: Calculations and results of the sensitivity analysis

Results sensitivity analysis simple model:

Varied parameter	P1	P2	Q1	Q2 [g CO2/pers-km]	Change in Output % (Q1-Q2)/((Q1+Q2)/2)	Change in Input % (P1-P2)/((P1+P2)/2)	η
Mode of transport	passenger car	urban bus	737.73	261.31			0.65
Fuel type	diesel	gasoline	737.73	981.02			-0.33
	diesel	natural gas/gasoline	737.73	759.01			-0.03
	diesel	liquid gas	737.73	779.95			-0.06
	diesel	E85	737.73	401.24			0.46
	diesel	electricity	737.73	532.60			0.28
Emission Standard	Euro 6	Euro 5	737.73	763.70			-0.04
	Euro 6	Euro 4	737.73	823.70			-0.12
	Euro 6	Euro 3	737.73	807.10			-0.09
	Euro 6	Euro 2	737.73	1062.92			-0.44
	Euro 6	Euro 1	737.73	905.28			-0.23
Cubic capacity	medium (1.4L - 2.0L)	small (<1.4L)	737.73	573.39			0.22
	medium (1.4L - 2.0L)	large (>2.0L)	737.73	964.38			-0.31
Distance					0.00%	0.00%	
	10.00	12.00	737.73	880.43	-17.64%	-18.18%	0.97
	10.00	14.00	737.73	1023.12	-32.41%	-33.33%	0.97
	10.00	16.00	737.73	1165.81	-44.98%	-46.15%	0.97

Occupancy rate					0.00%	0.00%	
	0.40	0.20	737.73	1475.47	-66.67%	66.67%	-1.00
	0.40	0.60	737.73	491.82	40.00%	-40.00%	-1.00
	0.40	0.80	737.73	368.87	66.67%	-66.67%	-1.00
	0.40	1.00	737.73	295.09	85.71%	-85.71%	-1.00
Well-to-tank emissions					0.00%	0.00%	
	Probas	Probas +20%	737.73	757.31	2.62%	18.18%	0.14
	Probas	Probas +40%	737.73	776.89	5.17%	33.33%	0.16
	Probas	Probas +60%	737.73	796.47	7.66%	46.15%	0.17
Tank-to-wheel emissions:					0.00%	0.00%	
	HBEFA	HBEFA +20%	737.73	880.43	17.71%	18.18%	0.97
	HBEFA	HBEFA +40%	737.73	1023.12	32.54%	33.33%	0.97
	HBEFA	HBEFA +60%	737.73	1165.81	45.14%	46.15%	0.97
Air conditioning:	yes	no	737.73	722.41			0.02
Cold start:	yes	no	737.73	713.47			0.03

Results sensitivity analysis medium model:

Varied parameter	P1	P2	Q1	Q2 [g CO2/pers-km]	Change in Output % (Q1-Q2)/((Q1+Q2)/2)	Change in Input % (P1-P2)/((P1+P2)/2)	η
Mode of transport	passenger car	urban bus	855.57	290.58			0.66
Fuel type	diesel	gasoline	855.57	1075.28			-0.26
	diesel	natural gas/gasoline	855.57	827.16			0.03
	diesel	liquid gas	855.57	849.98			0.01
	diesel	E85	855.57	449.43			0.47
	diesel	electricity	855.57	567.74			0.34
Emission Standard	Euro 6	Euro 5	855.57	889.00			-0.04
	Euro 6	Euro 4	855.57	963.25			-0.13
	Euro 6	Euro 3	855.57	953.45			-0.11
	Euro 6	Euro 2	855.57	1142.70			-0.34
	Euro 6	Euro 1	855.57	1071.14			-0.25
Cubic capacity	medium (1.4L - 2.0L)	small (<1.4L)	855.57	674.13			0.21
	medium (1.4L - 2.0L)	large (>2.0L)	855.57	1124.91			-0.31
Distance					0.00%	0.00%	
	10.00	12.00	855.57	1021.84	-17.71%	-18.18%	0.97
	10.00	14.00	855.57	1188.10	-32.54%	-33.33%	0.98
	10.00	16.00	855.57	1354.36	-45.14%	-46.15%	0.98
Occupancy rate					0.00%	0.00%	
	0.40	0.20	855.57	1711.15	-66.67%	66.67%	-1.00

	0.40	0.60	855.57	570.38	40.00%	-40.00%	-1.00
	0.40	0.80	855.57	427.79	66.67%	-66.67%	-1.00
	0.40	1.00	855.57	342.23	85.71%	-85.71%	-1.00
Well-to-tank emissions					0.00%	0.00%	
	Probas	Probas +20%	855.57	878.28	2.62%	18.18%	0.14
	Probas	Probas +40%	855.57	900.99	5.17%	33.33%	0.16
	Probas	Probas +60%	855.57	923.70	7.66%	46.15%	0.17
Tank-to-wheel emissions:					0.00%	0.00%	
	HBEFA	HBEFA +20%	855.57	1021.84	17.71%	18.18%	0.97
	HBEFA	HBEFA +40%	855.57	1188.10	32.54%	33.33%	0.98
	HBEFA	HBEFA +60%	855.57	1354.36	45.14%	46.15%	0.98
Air conditioning:	yes	no	855.57	828.31			0.03
Traffic situation:	urban	rural	855.57	640.90			0.25
	urban	highway	855.57	741.11			0.13
Cold start:	yes	no	855.57	831.31			0.03

Results sensitivity analysis detailed model:

Varied parameter	P1	P2	Q1	Q2 [g CO2/pers-km]	Change in Output % (Q1-Q2)/((Q1+Q2)/2)	Change in Input % (P1-P2)/((P1+P2)/2)	η
Mode of transport	passenger car	urban bus	615.58	169.73			0.72
Fuel type	diesel	gasoline	615.58	791.99			-0.29
	diesel	natural gas/gasoline	615.58	606.85			0.01
	diesel	liquid gas	615.58	623.59			-0.01
	diesel	E85	615.58	318.83			0.48
	diesel	electricity	615.58	433.18			0.30
Emission Standard	Euro 6	Euro 5	615.58	635.75			-0.03
	Euro 6	Euro 4	615.58	683.68			-0.11
	Euro 6	Euro 3	615.58	665.99			-0.08
	Euro 6	Euro 2	615.58	877.53			-0.43
	Euro 6	Euro 1	615.58	746.97			-0.21
Cubic capacity	medium (1.4L - 2.0L)	small (<1.4L)	615.58	474.94			0.23
	medium (1.4L - 2.0L)	large (>2.0L)	615.58	801.11			-0.30
Distance					0.00%	0.00%	
	10.00	12.00	615.58	733.84	-17.53%	-18.18%	0.96
	10.00	14.00	615.58	852.11	-32.23%	-33.33%	0.97
	10.00	16.00	615.58	970.37	-44.74%	-46.15%	0.97

Occupancy rate	0.40	0.20	615.58	1231.16	-66.67%	-66.67%	1.00
					0.00%	0.00%	
	0.40	0.60	615.58	410.39	40.00%	40.00%	1.00
	0.40	0.80	615.58	307.79	66.67%	66.67%	1.00
	0.40	1.00	615.58	246.23	85.71%	85.71%	1.00
Well-to-tank emissions					0.00%	0.00%	
	Probas	Probas +20%	615.58	631.92	2.62%	18.18%	0.14
	Probas	Probas +40%	615.58	648.26	5.17%	33.33%	0.16
	Probas	Probas +60%	615.58	664.59	7.66%	46.15%	0.17
Tank-to-wheel emissions:					0.00%	0.00%	
	HBEFA	HBEFA +20%	615.58	733.84	17.53%	18.18%	0.96
	HBEFA	HBEFA +40%	615.58	852.11	32.23%	33.33%	0.97
	HBEFA	HBEFA +60%	615.58	970.37	44.74%	46.15%	0.97
Air conditioning:	yes	no	615.58	606.25			0.02
Traffic situation (level of service):	/Land/AB/80/flüssig	/Land/AB/80/dicht	615.58	591.91			0.04
	/Land/AB/80/flüssig	/Land/AB/80/gesättigt	615.58	685.24			-0.11
	/Land/AB/80/flüssig	/Land/AB/80/stop+go	615.58	1066.84			-0.73
Traffic situation (area):	/Land/AB/80/flüssig	/Agglo/AB/80/fluessig	615.58	586.01			0.05
Traffic situation					0.00%	0.00%	

(speed limit):							
	/Land/AB/80/flüssig	/Land/AB/90/fluessig	615.58	609.38	-1.01%	11.76%	-0.09
	/Land/AB/80/flüssig	/Land/AB/100/fluessig	615.58	622.84	1.17%	22.22%	0.05
	/Land/AB/80/flüssig	/Land/AB/110/fluessig	615.58	683.22	10.42%	31.58%	0.33
	/Land/AB/80/flüssig	/Land/AB/120/fluessig	615.58	725.87	16.44%	40.00%	0.41
	/Land/AB/80/flüssig	/Land/AB/130/fluessig	615.58	773.70	22.76%	47.62%	0.48
	/Land/AB/80/flüssig	/Land/AB/>130/fluessig	615.58	860.14	33.14%	54.55%	0.61
Gradient:					0.00%	0.00%	
	0%	±2%	615.58	599.99	-2.57%	200.00%	-0.01
		±4%	615.58	617.72	0.35%	200.00%	0.00
		±6%	615.58	690.93	11.53%	200.00%	0.06
Cold start:	yes	no	615.58	591.31			0.04

Annex 8: MiT data used for the development of the storylines

R: Gemeindegröße	MiT Abfrage	3-PersonenHH	HH mit mind. 1 Kind unter 6	HH mind. 1 Kind unter 14	HH mit mind. 1 Kind unter 18	Mittelwert:
20.000 bis 50.000 Einw.	Datentabelle **Haushaltsdaten**, Zeile **R: Gemeindegröße**, Spalte **HH: Haushaltstyp**, Mittelwert für HH: Anzahl Autos im Haushalt, Darstellung **Mittelwerte über alle Haushalte**	2.1	1.5	1.7	1.8	1.775
20.000 bis 50.000 Einw.	Datentabelle **Wegedaten**, Zeile **R: Gemeindegröße**, Spalte **HH: Haushaltstyp**, Mittelwert für W: Wegelänge in Kilometern, Darstellung **Mittelwerte über alle Wege**	13.8	10.1	10.2	9.6	10.925
20.000 bis 50.000 Einw.	Datentabelle **Personendaten**, Zeile **R: Gemeindegröße**, Spalte **HH: Haushaltstyp**, Mittelwert für P: Anzahl Wege am Stichtag, Darstellung **Mittelwerte über alle Personen**	3.2	3.6	3.6	3.5	3.475
20.000 bis 50.000 Einw.	Datentabelle **Personendaten**, Zeile **R: Gemeindegröße**, Spalte **HH: Haushaltstyp**, Mittelwert für P: Tagesstrecke (km/ Person), Darstellung **Mittelwerte über alle Personen**	43.5	36.1	36.8	33.9	37.575
20.000 bis 50.000 Einw.	Datentabelle **Personendaten**, Zeile **R: Gemeindegröße**, Spalte **HH: Haushaltstyp**, Mittelwert für P: Unterwegszeit (Min/Person), Darstellung **Mittelwerte über alle Personen**	76.5	73.6	71.9	73.4	73.85

Annex 9: Storylines

Storyline realistic scenario:

Time	Trip purpose	Distance [km]	Passengers	Mode of transport	Speed [km/h]:	Duration [Min]:
07:15 - 08:14	Father travels to work	30	Father	Main car	30.4	59
07:30 - 07:44	Daughter travels to school	1	Daughter	By foot	4.4	14
07:25 - 07:42	Son travels to school	7	Son	Bus	25.3	17
12:10 - 12:24	Daughter travels home from school	1	Daughter	By foot	4.4	14
13:10 - 13:27	Son travels home from school	7	Son	Bus	25.3	17
15:00 - 15:20	Mother brings son to soccer practice	10	Mother, son	Electric car	30.4	20
15:25 - 15:35	Mother travels to the mall	5	Mother	Electric car	30.4	10
16:15 - 16:25	Mother travels from the mall to the soccer field	5	Mother	Electric car	30.4	10
16:30 - 16:50	Mother brings son home	10	Mother, son	Electric car	30.4	20
17:00 - 17:59	Father travels home from work	30	Father	Main car	30.4	59
19:00 - 19:33	Father travels to the gym	6	Father	Bike	10.8	33
20:30 - 21:03	Father travels home from the gym	6	Father	Bike	10.8	33

Storyline optimistic scenario:

Time	Trip purpose	Distance [km]	Passengers	Mode of transport	Speed [km/h]:	Duration [Min]:
07:15 - 08:14	Father travels to work	30	Father	Electric car	30.4	59
07:30 - 07:44	Daughter travels to school	1	Daughter	By foot	4.4	14
07:25 - 07:42	Son travels to school	7	Son	Bus	25.3	17
12:10 - 12:24	Daughter travels home from school	1	Daughter	By foot	4.4	14
13:10 - 13:27	Son travels home from school	7	Son	Bus	25.3	17
15:00 - 15:24	Son travels to soccer practice	10	Son	Bus	25.3	24
15:25 - 15:31	Mother travels to the supermarket	1	Mother	Bike	10.8	6
16:15 - 16:21	Mother travels home from the supermarket	1	Mother	Bike	10.8	6
16:30 - 16:54	Son travels home from soccer practice	10	Son	Bus	25.3	24
17:00 - 17:59	Father travels home from work	30	Father	Electric car	30.4	59
19:00 - 19:33	Father travels to the gym	6	Father	Bike	10.8	33
20:30 - 21:03	Father travels home from the gym	6	Father	Bike	10.8	33

Storyline pessimistic scenario:

Time	Trip purpose	Distance [km]	Passengers	Mode of transport	Speed [km/h]:	Duration [Min]:
07:15 - 08:14	Father travel to work	30	Father	Main car	30.4	59
07:30 - 07:46	Mother brings kids to school	8	Mother, son, daughter	Electric car	30.4	16
07:25 - 07:39	Mother travels home	7	Mother	Electric car	30.4	14
12:10 - 12:26	Mother travels to school	8	Mutter	Electric car	30.4	16
13:10 - 13:24	Mother brings the kids home	7	Mother, son, daughter	Electric car	30.4	14
15:00 - 15:20	Mother brings son to soccer practice	10	Mother, son	Electric car	30.4	20
15:25 - 15:35	Mother travels to the mall	5	Mother	Electric car	30.4	10
16:15 - 16:25	Mother travels from the mall to the soccer field	5	Mother	Electric car	30.4	10
16:30 - 16:50	Mother brings son home	10	Mother, son	Electric car	30.4	20
17:00 - 17:59	Father travels home from work	30	Father	Main car	30.4	59
19:00 - 19:12	Father travels to the gym	6	Father	Electric car	30.4	12
20:30 - 20:42	Father travels home from the gym	6	Father	Electric car	30.4	12

Annex 10: Calculation results for the model

Baseline Scenario

	Personenbezogene CO2 Emission [g CO2/Pers]	Verkehrsmittel	Distanz	Besetzungsgrad	Kraftstoff
Familienmitglied_1	11992.43075		60	20.00%	
Weg 1	5996.215376	PKW Diesel >=2L Euro-5 DPF	30	20.00%	Diesel
Weg 2	5996.215376	PKW Diesel >=2L Euro-5 DPF	30	20.00%	Diesel
Familienmitglied_2	3255.987013		30	33.33%	
Weg 1	1627.993506	PKW Diesel 1.4-<2L Euro-4 (DPF)	15	33.33%	Diesel
Weg 2	1627.993506	PKW Diesel 1.4-<2L Euro-4 (DPF)	15	33.33%	Diesel
Familienmitglied_3	2256.994468		34	33.82%	
Weg 1	304.7943849	LBus Standard >15-18t Euro-III	7	25.00%	Diesel
Weg 2	304.7943849	LBus Standard >15-18t Euro-III	7	25.00%	Diesel
Weg 3	823.7028491	PKW Diesel 1.4-<2L Euro-4 (DPF)	10	40.00%	Diesel
Weg 4	823.7028491	PKW Diesel 1.4-<2L Euro-4 (DPF)	10	40.00%	Diesel
Familienmitglied_4	Für dieses Familienmitglied wurde kein Weg ausgewählt!		0		

Realistic Scenario

	Personenbezogene CO2 Emission [g CO2/Pers]	Verkehrsmittel	Distanz	Besetzungsgrad	Kraftstoff
Familienmitglied_1	11992.43075		60	0.2	
Weg 1	5996.215376	PKW Diesel >=2L Euro-5 DPF	30	0.2	Diesel
Weg 2	5996.215376	PKW Diesel >=2L Euro-5 DPF	30	0.2	Diesel
Familienmitglied_2	1247.078456		30	0.333333333	
Weg 1	623.5392282	Elektroauto mittel	15	0.333333333	Strom (50% Mix. 50% PV)
Weg 2	623.5392282	Elektroauto mittel	15	0.333333333	Strom (50% Mix. 50% PV)
Familienmitglied_3	1233.127998		34	0.338235294	
Weg 1	304.7943849	LBus Standard >15-18t Euro-III	7	0.25	Diesel
Weg 2	304.7943849	LBus Standard >15-18t Euro-III	7	0.25	Diesel
Weg 3	311.7696141	Elektroauto mittel	10	0.4	Strom (50% Mix. 50% PV)
Weg 4	311.7696141	Elektroauto mittel	10	0.4	Strom (50% Mix. 50% PV)
Familienmitglied_4	Für dieses Familienmitglied wurde kein Weg ausgewählt!		0		

Optimistic Scenario

	Personenbezogene CO2 Emission [g CO2/Pers]	Verkehrsmittel	Distanz	Besetzungsgrad	Kraftstoff
Familienmitglied_1	3741.235369		60	0.2	
Weg 1	1870.617684	Elektroauto mittel	30	0.2	Strom (50% Mix. 50% PV)
Weg 2	1870.617684	Elektroauto mittel	30	0.2	Strom (50% Mix. 50% PV)
Familienmitglied_2	Für dieses Familienmitglied wurde kein Weg ausgewählt!		0		
Familienmitglied_3	1480.42987		34	0.25	
Weg 1	304.7943849	LBus Standard >15-18t Euro-III	7	0.25	Diesel
Weg 2	304.7943849	LBus Standard >15-18t Euro-III	7	0.25	Diesel
Weg 3	435.4205499	LBus Standard >15-18t Euro-III	10	0.25	Diesel
Weg 4	435.4205499	LBus Standard >15-18t Euro-III	10	0.25	Diesel
Familienmitglied_4	Für dieses Familienmitglied wurde kein Weg ausgewählt!		0		

Pessimistic Scenario

	Personenbezogene CO2 Emission [g CO2/Pers]	Verkehrsmittel	Distanz	Besetzungsgrad	Kraftstoff
Familienmitglied_1	12740.67783		72	20.00%	
Weg 1	5996.215376	PKW Diesel >=2L Euro-5 DPF	30	20.00%	Diesel
Weg 2	5996.215376	PKW Diesel >=2L Euro-5 DPF	30	20.00%	Diesel
Weg 3	374.1235369	Elektroauto mittel	6	20.00%	Strom (50% Mix. 50% PV)
Weg 4	374.1235369	Elektroauto mittel	6	20.00%	Strom (50% Mix. 50% PV)
Familienmitglied_2	2348.664426		60	36.67%	
Weg 1	675.5008305	Elektroauto mittel	15	32.00%	Strom (50% Mix. 50% PV)
Weg 2	426.0851392	Elektroauto mittel	15	48.00%	Strom (50% Mix. 50% PV)
Weg 3	623.5392282	Elektroauto mittel	15	33.33%	Strom (50% Mix. 50% PV)
Weg 4	623.5392282	Elektroauto mittel	15	33.33%	Strom (50% Mix. 50% PV)
Familienmitglied_3	1008.055086		35	44.57%	
Weg 1	239.0233708	Elektroauto mittel	8	42.50%	Strom (50% Mix. 50% PV)
Weg 2	145.4924866	Elektroauto mittel	7	60.00%	Strom (50% Mix. 50% PV)
Weg 3	311.7696141	Elektroauto mittel	10	40.00%	Strom (50% Mix. 50% PV)
Weg 4	311.7696141	Elektroauto mittel	10	40.00%	Strom (50% Mix. 50% PV)
Familienmitglied_4	384.5158574		15	50.67%	
Weg 1	20.78464094	Elektroauto mittel	1	60.00%	Strom (50% Mix. 50% PV)
Weg 2	363.7312164	Elektroauto mittel	14	50.00%	Strom (50% Mix. 50% PV)

Variation of different parameters

Electricity mix for the realistic scenario

Family member	50% PV, 50% German grid mix	100% German grid mix	25% PV, 75% German grid mix	75% PV, 25% German grid mix	100% PV
Father	11992,4308	11992,4308	11992,4308	11992,4308	11992,4308
Mother	1247,07846	2130,40826	1688,74336	805,413553	363,748651
Son	1233,128	1674,7929	1453,96045	1012,29555	791,463095
Daughter	0	0	0	0	0
Sum:	14472,6372	15797,6319	15135,1346	13810,1399	13147,6425

Changes in occupancy rate for the first car

Family member	Baseline Scenario	Occupancy rate 40% for first car	Occupancy rate 60% for first car	Occupancy rate 80% for first car	Occupancy rate 100% for first car
Father	11992.43	5996.21538	3792.81447	2998.10769	2398.48615
Mother	3255.99	3255.99	3255.99	3255.99	3255.99
Son	2256.99	2256.99	2256.99	2256.99	2256.99
Daughter	0	0	0	0	0
Sum:	17505.41	11509.1954	9305.79447	8511.08769	7911.46615

Change in occupancy rate for the public bus

Family member	Baseline Scenario	Occupancy rate 40% for first car
Father	11992.43	5996.21538
Mother	3255.99	3255.99
Son	2256.99	2256.99
Daughter	0	0
Sum:	17505.41	11509.1954

Change of public bus from diesel to CNG

Family member	Baseline Scenario	Public bus CNG instead of diesel
Father	11992.43	11992.43
Mother	3255.99	3255.99
Son	2256.99	2277.09
Daughter	0	0
Sum:	17505.41	17525.51

Change of OR for soccer practice

Family member	Baseline Scenario	OR soccer practice changed
Father	11992.43	11992.43
Mother	3255.99	2512.12
Son	2256.99	1534.61
Daughter	0	0
Sum:	17505.41	16039.15

Change of first car from large Euro V to medium and small Euro VI

Family member	Baseline Scenario	First car: large V → medium VI	First car: large V → small VI
Father	11992.43	8658.67	6686.53
Mother	3255.99	3255.99	3255.99
Son	2256.99	2256.99	2256.99
Daughter	0	0	0
Sum:	17505.41	14171.65	12199.52

Change of second car from medium Euro IV to small Euro VI

Family member	**Baseline Scenario**	**Second car: medium IV → small VI**
Father	11992.43	11992.43
Mother	3255.99	2254.73
Son	2256.99	1756.36
Daughter	0	0
Sum:	17505.41	16003.52

Eidesstattliche Erklärung

Hiermit versichere ich eidesstattlich, dass ich die vorliegende Arbeit selbständig und ohne Benutzung anderer als der angegebenen Hilfsmittel angefertigt habe. Alle Stellen, die wörtlich oder sinngemäß aus Veröffentlichungen entnommen sind, wurden als solche kenntlich gemacht.

Die Arbeit wurde in gleicher oder ähnlicher Form keiner anderen Prüfungsbehörde vorgelegt.

München, 10. Oktober 2013

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Edina Löhr