Analysis of survey data on preferences of German commuters using structural equation modeling

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ABSTRACT

The transport landscape in Germany is facing serious changes. A steadily increasing demand meets a road network that has hardly been expanded in recent years and will not be expanded in the future. One way out of this problem situation can be managed lanes, which enable a more efficient use of the existing road space. Specifically, this paper looks at the potential of HOV lanes and HOT lanes in Germany. For this purpose, the methodology of structural equation modeling, which has not been used in transportation science before, is also applied.

The results show that both carpooling for HOV lanes has considerable potential in Germany and that there is a willingness to pay additional fees to use free capacities of an HOV lane and thus make it a HOT lane. However, this willingness is linked to clear expectations of personal benefits, for example in the form of travel time gains. In addition, commuters were able to identify desired framework conditions for their commute.

The structural equation modeling method used has proven its worth in the context of this work. We therefore see considerable potential in this method, which is able to determine latent variables and to show dependencies between different measured variables. Additional information could be obtained from the available data. For example, it was possible to show which influencing factors have the strongest impact on the choice of means of transport for the commute to work and which framework conditions only play a subordinate role.

Keywords: Managed Lanes, Europe, traffic management

INTRODUCTION

Almost 75% of the working population in Germany has a daily commute of more than 5 km (*1*). More than half of them spend between 10 and 30 minutes traveling to work, while more than one in five have a commute between 30 and 60 minutes (*1*). Thus, for many people, the commute to work is a central part of their daily life. Around 68% of workers' commutes are completed via private car, a travel mode with an occupancy rate of 1.2 persons /car (*2*). Especially in metropolitan areas and their immediate surroundings, private-car commutes and related phenomenon are contributing to steadily growing traffic volumes and infrastructures that are at the limits of their load-bearing capacity. This ultimately leads to veritable traffic jams and congestion. Despite the worsening traffic situation, the number of people traveling by private car continues to rise, while the number of people using public transportation has stagnated or even declined in recent years (*3*). Even a significant increase in environmental awareness in recent years and higher prices for conventionally-fueled vehicles have not changed this situation.

One way to optimize traffic in the future is through the managed lanes approach. Two particularly promising managed lanes approaches in Germany that could be used are increasing the proportion of carpools and charging for lanes, since the use of roads in Germany is currently free of charge.

Carpooling is a simple means of reducing individual travel costs since, for example, fuel costs would no longer have to be borne by the driver alone and improved traffic flow would enable the driver to reach his or her destination more quickly. Nevertheless, the number of carpool users is stagnating. Dynamic pricing of lanes depending on the time of day, pollutant class or occupancy level, for example, can have a considerable traffic-steering effect and thus buffer peak loads.

To find out what travel characteristics are important for commuters in Germany and what general conditions they would like to see, a survey was conducted. The central questions of the survey were whether there is a basic willingness to pay for the use of express lanes and, if so, under what circumstances the travelers could imagine carpooling, and which travel options would be chosen under certain general conditions.

In addition to the classic methods of statistical analysis of the survey, such as contingency tabulation, ANOVA evaluations, or simple descriptive observations, analysis using structural equation modeling is the central element of this paper. Structural equation models are currently used mainly in social sciences, humanities, and economics, but they also offer interesting options for transportation. They can be used to determine and present causalities between different variables in a clear and comprehensive way.

This paper is structured as follows. After a brief state of the art, the survey conducted and its results are presented. Subsequently, the methodology of structural equation modeling is introduced and the data obtained in the survey is analyzed using this technique. Finally, an interpretation of the results and an outlook on the further procedure of the authors follows.

MOTIVATION

Limited financial resources, conflicts of use, stricter nature conservation and environmental protection legislation, as well as the expansion and new construction of German roads have largely come to a standstill in recent years. On the other hand, however, traffic figures are steadily increasing, especially in the vicinity of major cities. Germany is not alone in this problem; in other European countries, too, traffic figures are rising much faster than the capacities of the routes are being adapted (*4*). Against this background, traffic engineering and traffic control measures are becoming enormously important in order to handle traffic more efficiently on the existing route network. Managed lanes can play a central element in this. Germany already uses hard shoulder running and ramp metering on large sections of road, and variable message signs are also being used on a larger scale, which are also being promoted as part of the Intelligent Transport Systems Directive (ITS) being promoted by the EU.

However, the efforts made to date are not yet sufficient to ensure safe and flowing traffic throughout Germany. Here, the HOV lanes and HOT lanes already being intensively tested in America could be a next step. These have not yet been used in Germany. In order to find out what acceptance such a system would have in Germany, a survey was developed by the Technical University of Munich in cooperation with the Baden-Württemberg Cooperative State University. The aim of the survey is to find out what is important to commuters in Germany, what they would be willing to do without under certain circumstances, and what potential lies in carpooling, for example. This data is important as a basis for future research, in which, for example, the demand for transport in new transport systems must be forecast and demand optimized.

To analyze the data obtained, structural equation modeling is used in addition to the classical methods commonly used in transportation science. The authors became aware of this method during an interdisciplinary exchange. After discussions with colleagues from other disciplines, we believe that this powerful method in data analysis and statistics also has great potential in the field of transportation science. However, in previous research, no transport science publications on this methodology were found, so in the second part of the paper we want to approach SEM by means of a limited data set and check whether SEM is also promising for our field of research.

THE SURVEY

The survey was conducted via the Microsoft Forms platform and advertised via Facebook and other Meta Group and LinkedIn offerings, among others. The questionnaire follows a classic structure and, in addition to their socio-demographic background, asks participants about their preferences for commuting to work. This is done by means of decision questions for various scenarios in which the participants have to decide on a transport option under given framework conditions, as well as specific questions about the importance of framework conditions such as costs, flexibility and travel time, for example. All evaluations presented here are stochastically significant.

A total of 212 participants were recruited for the survey. Of these, 111 persons assigned themselves to the female gender and 101 persons indicated male as their gender; the option "diverse" was not selected. Figure 1 shows the age distribution of the survey participants. There is a clear focus on the age group between 21 and 30 years. This is due to various factors. The platforms of the Meta Group and LinkedIn primarily serve people under 40 years of age, while the survey also explicitly sought commuters, a population group whose age tends to skew younger. Overall, the authors consider the survey sample to be representative.

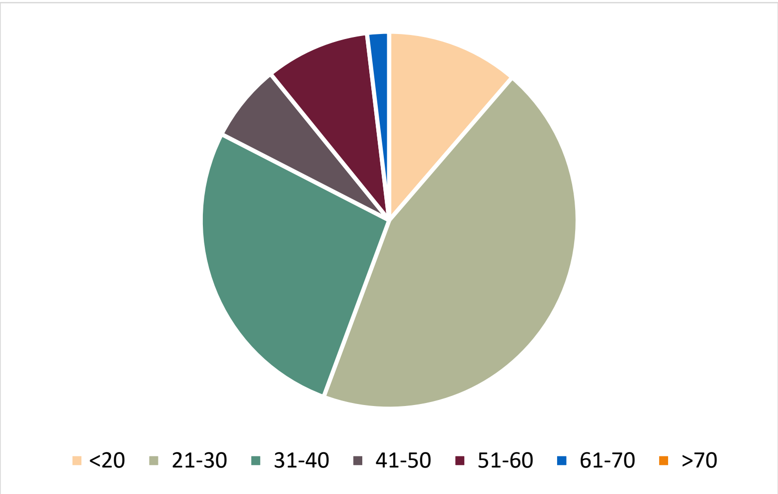

Figure 1: Age distribution of participants in the survey

When asked whether they would rate their disposable household income as average, above, or below average, 48% of respondents reported an average income. Interestingly, however, more than twice as many respondents (34%) considered themselves to be in the above-average income group than in the below-average group (only 16%). 2% of the participants did not want to provide any information. It could not be verified in this study why the figures for those who describe themselves as above-average earners are so surprisingly high. Possible explanations could be that there is a certain shame in disclosing one's low income to third parties and therefore there is a general tendency to overestimate one's income, or that there is currently a relatively prominent discussion in Germany about the minimum wage sector, which makes one's own household income appear larger in comparison. Furthermore, the survey could have unintentionally encouraged or discouraged certain groups to participate.

When asked about their type of residence, 44% of respondents said they lived in rural areas or in small towns with up to 15,000 inhabitants. Just under 35% of respondents live in urban areas, i.e. cities with more than 60,000 inhabitants, and only 21% said they lived in suburbs or medium-sized cities. In contrast, when it came to job location, 44% of respondents said they work in urban areas, while 32% reported working in suburbs and mid-sized cities, and only 24% of people had jobs in rural areas or small towns. This clearly shows that jobs are concentrated in cities, while many people move to the surrounding areas for housing. The reasons for this are varied and, in the case of housing, range from cost to emotional ties with the home region, which are often accompanied by family ties. Companies, on the other hand, often take advantage of synergies resulting from the accumulation of companies in cities. The location of residences and workplaces is also reflected in public transportation connections; only 54% said they could get to work in a decent time by public transport, while 46% said they could not.

Figure 2 shows the distances covered by the participants in this survey on their way to work. A rough three-way split is discernible. Around one in three commuters travels between 10 and 30 kilometers on their way to work. Likewise, around a third each travel less than 10 kilometers and more than 30 kilometers.

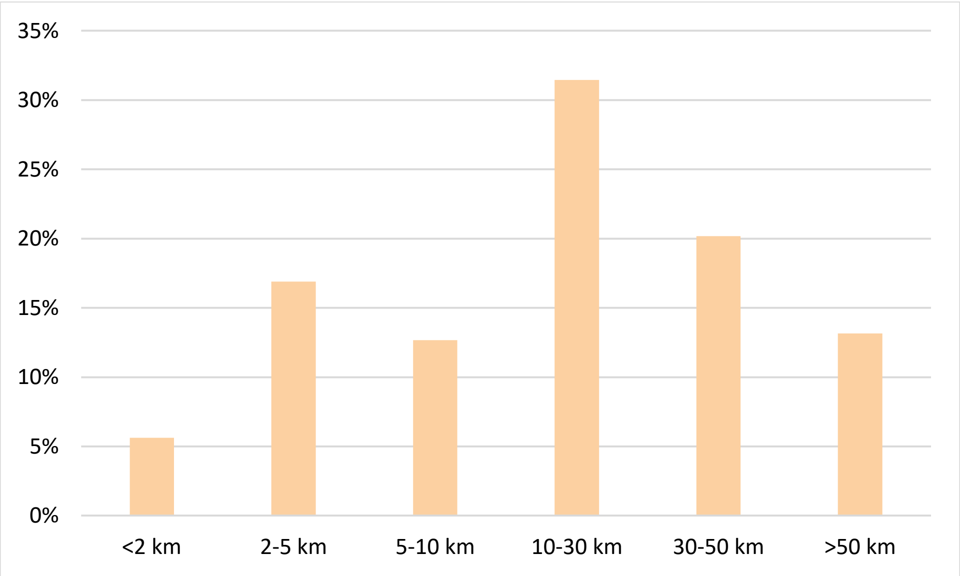

Figure 2: Commuting distance

The vast majority of commuters cover these distances in less than an hour. In this context, 14% of respondents reach their destination in less than 10 minutes, while 19% need 10 - 20 minutes. Most frequently, namely 22% of the respondents in each case, stated their travel time as 20 - 30 minutes or 30 - 45 minutes. Additionally, 17% of respondents require 45 - 60 minutes to get to work, while only 7% stated a commute of over an hour.

Findings from the survey on car-pooling

As of this reporting, only 18% of respondents use carpooling at least occasionally, while 82% do not consider carpooling as a travel option. Among those who carpool at least occasionally, around a quarter use this option less than once a week on average but at least once a month. More than one in three of these respondents carpool to the office once or twice a week. The potential here is revealed by the question of the conditions under which respondents would enter a carpool. Only 10% said they would not want to carpool in principle, while the rest were open to this option, albeit sometimes under very challenging conditions such as halving their commuting time. What is striking here is that people who today have a very short to short commute and currently do not use carpools state that they would be willing to carpool in the future and do not expect any benefits in return, such as travel time gains, but would already be satisfied with socioeconomic benefits such as shared rides with friends or a more ecological commute. On the other hand, a clear majority of people who already commute expect significant travel time benefits for the joint trip to work.

Looking at the data, it is clear that the number of people who use carpooling increases with increasing route length. Figure 3 shows the proportion of those who carpool at least occasionally. For commutes of more than 10 km, more than one in five commuters carpool at least occasionally; this figure rises to around 28% for distances of 30 km and more, and then stagnates at this level for even longer distances.

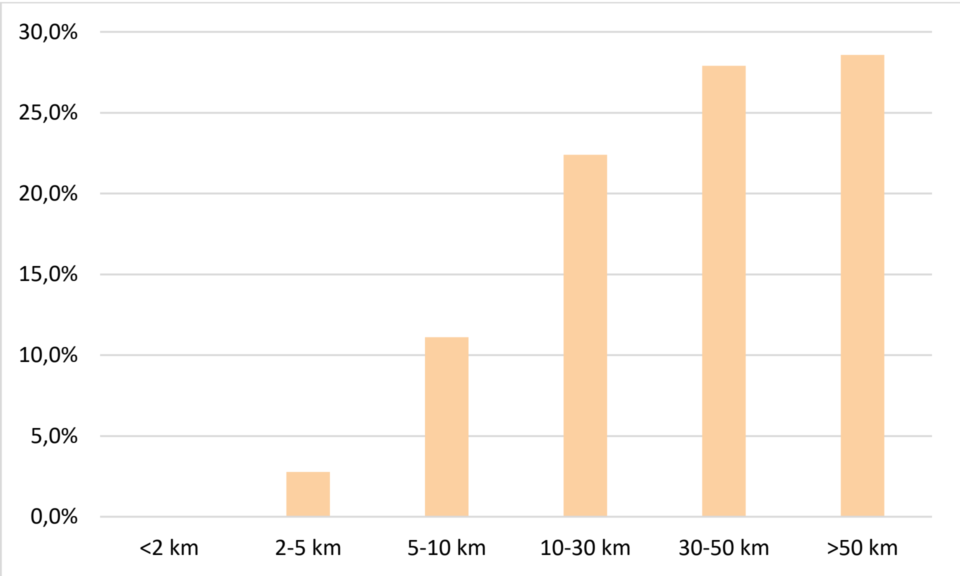

Figure 3: Car-pooling vs. way to work

Faced with the choice of forming a fixed carpool, in which the same people share a vehicle every day but sacrifice flexibility, or spontaneous carpools with alternating passengers who currently have similar departure times and locations and are therefore more flexible and, overall, faster, only 26% choose spontaneous carpools. Here, however, it is interesting to look at the gender breakdown. While 40% of men would opt for spontaneous carpooling, only just over one in seven women can imagine utilizing the spontaneous, faster, and more flexible option.

For carpooling, it is important that there is an adequate public transport connection on site. It is hardly surprising that people who can reach their workplace in a reasonable amount of time by public transport are less likely to carpool. In the current survey, 24% of those who do not currently have public transport access say they carpool at least occasionally. This figure is ten percentage points lower if public transport is considered at least adequate. Interestingly, the presence of good public transport also affects voting decisions for fictitious scenarios in the future. For different fictitious scenarios with given travel times and costs, participants were asked to choose how often per week they would carpool, pay money for an express lane, use public transit, or accept an extended travel time at no additional cost under the given constraints. Here, it was shown that if public transportation was available, 80% of participants would choose public transportation to get to work at least one day a week, while only 44% of people without current public transport connections considered it an option in the fictitious scenarios. This shows the potential of an expansion of public transport.

As part of the survey, the participants were asked to sort the aspects of travel costs, travel time, ecology/environmental protection, and social benefits in descending order of importance for the commute. The results are shown in Figure 4.

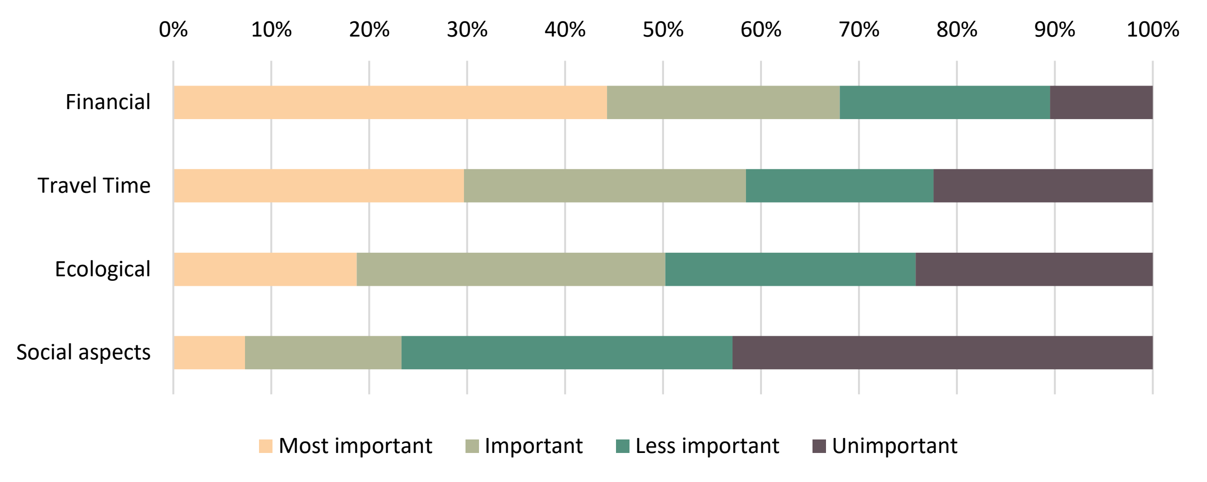

Figure 4: Importance of different topics in commuting

Overall, 44% of respondents rated monetary travel costs as the most important influencing factor, while travel time was the main factor for only 30%. By contrast, environmental issues and social aspects, such as sharing a ride with friends/acquaintances, play a subordinate role when it comes to the most important topic in commuting to work. However, it is striking that the environmental aspect is the second most frequently mentioned component at 32%. Overall, the topics of price, travel time and the environment are rated as very important or important by more than 50% of the participants; only the social component of carpooling fails to meet this threshold, with more than three out of four respondents considering the topic to be of secondary importance.

Findings from the survey on preferences

As part of the survey, participants were asked to indicate how many days per week they would choose a specific transport mode given different scenarios. The baseline scenario was the same each time. Participants were asked to imagine that it currently takes them 45 minutes to get to work in the morning, but that a new HOT lane would enable them to reduce their travel time in the future. The use of the HOT lane was priced from €5 to €20, and the travel time could be reduced from 45 minutes to 25 to 35 minutes. Overall, the following modes of transportation were available:

- Carpooling with travel time improvements and free use of the HOT lane.

- SOP ride with paid use of the HOT lane

- Switching to public transport with comparable conditions to carpooling

- SOP trip without using the HOT lane with extended travel time

It became clear that the willingness to pay decreases with increasing costs and, at the same time, a higher willingness to pay is associated with an increasing reduction in travel time.

Figure 5 shows an example of how the willingness to pay decreases with higher prices and lower travel time gains.

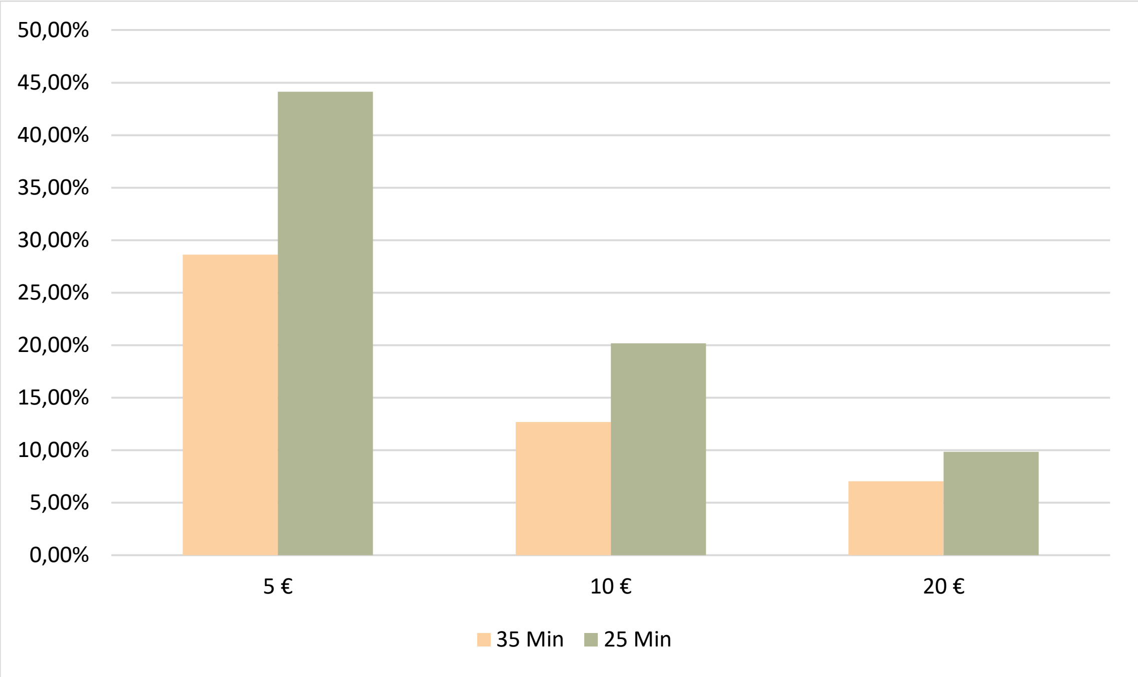

Figure 5: Willingness to pay

The figure above shows that 44% of respondents could at least occasionally imagine paying €5 to use an express lane if they could reduce their travel time from 45 to 25 minutes. In the case that the travel time could be reduced by only 10 minutes to 35 minutes, the willingness to pay at least occasionally drops to 28%. Likewise, willingness to pay decreases significantly with increasing costs, to just 7% for a 10-minute travel time advantage at a cost of €20.

In contrast, the survey shows no correlation between travel time and costs and the choice of public transport. The number of users remained constant across all scenarios and did not respond to increased costs or decreased travel times.

Surprisingly, the decision whether to carpool was also independent of travel costs and travel times. Here, it would have been expected that lower travel times would lead to an increased use of carpooling. However, this is not observed in the data. Rather, the number of those who can imagine carpooling at least occasionally on their way to work is consistent regardless of travel time.

Disposable household income has a significant influence on the willingness to pay for using a HOT lane. Figure 6 shows how the willingness to pay for an express lane changes based on income group. The figure is divided based on travel times of 35 minutes on the left side and 25 minutes on the right. It becomes clear that, especially with moderate HOT lane fees of €5, there is a high willingness among above-average earners to pay for a shorter travel time. This willingness is significantly higher than that among the other income groups. In contrast, there are only very slight differences in willingness to pay between the average and below-average income groups. In some cases, the willingness-to-pay values are even higher among users with below-average incomes than among those with average incomes, but this may also be due to longer commutes or the relatively small size of the reference group.

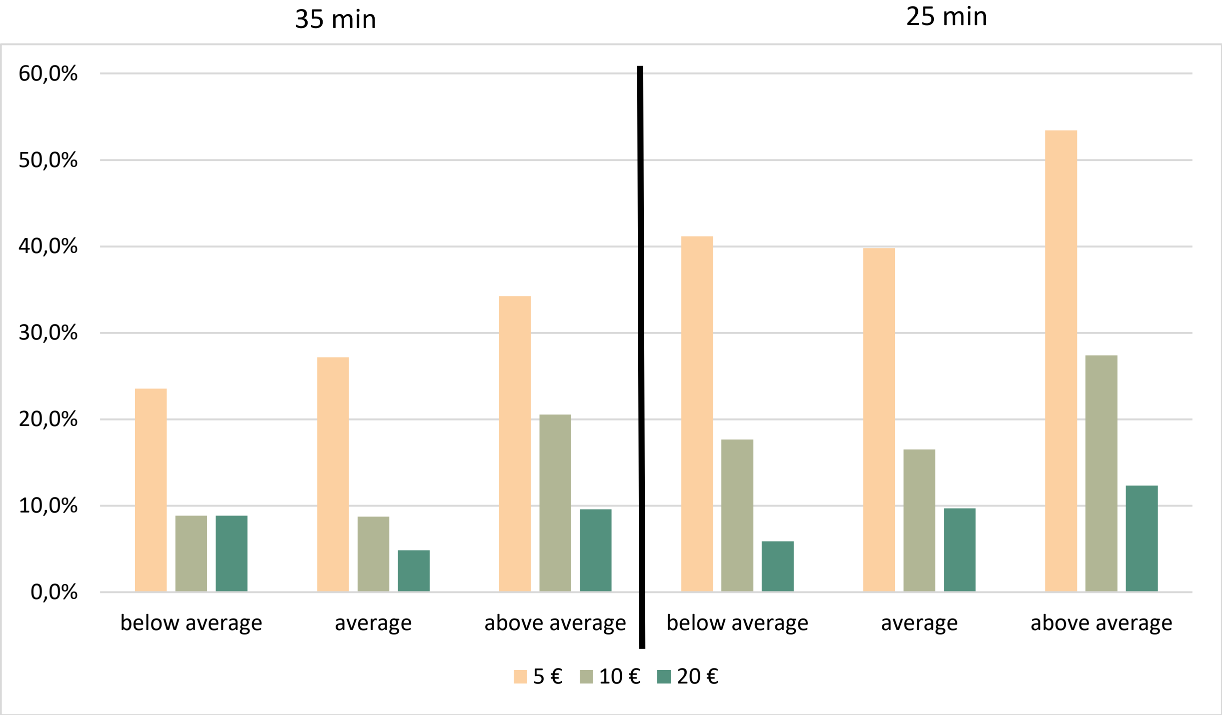

Figure 6: Willingness to pay - Income

The importance of flexibility increases with higher income, as Figure 7 shows. Although more than 50% of all income groups state that flexibility is important or rather important to them, the figure varies significantly between income groups. 58% of the people with below-average incomes declare flexibility as important or rather important, while 73% of the people with above-average incomes vote for this option. Specifically, when comparing the individual percentages, the percentage of those who consider flexibility to be important, at over 40% for the above-average earners, is significantly higher than that of the other income groups, where, for example, only 14% of people with below-average incomes stated that flexibility was important to them. At the other end of the scale, none of above-average earners said that flexibility was unimportant to them, while as many as 15% of those with low incomes did not attach any importance to flexibility.

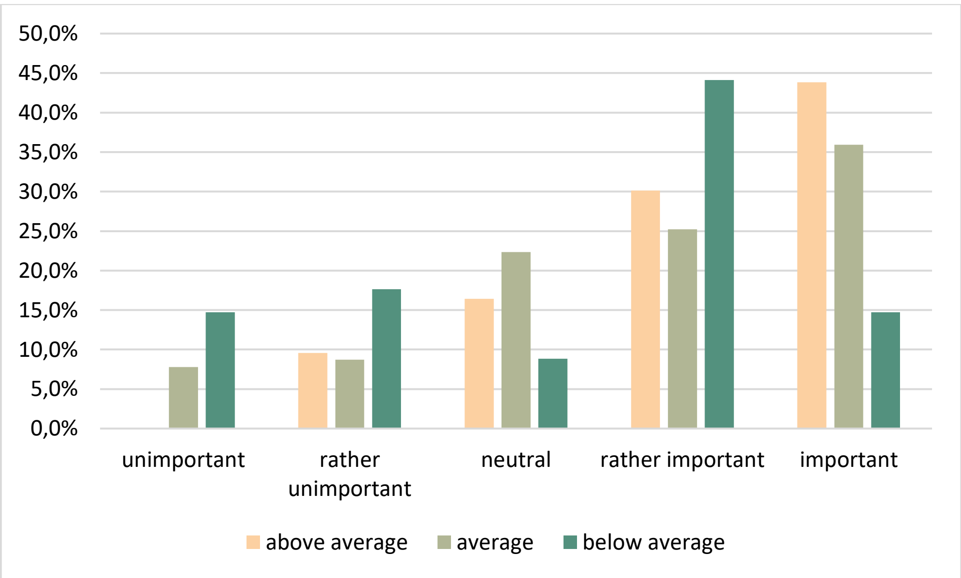

Figure 7: Importance of flexibility

After considering the above results, it is not surprising if, when evaluating the data regarding the importance of travel costs as a function of disposable household income, there is a negative relationship between the importance of travel costs and disposable household income. Only 7% of wealthier households see travel costs as important, but for 28% they are unimportant or somewhat unimportant. In contrast, travel costs are a key issue for 41% of poorer households and still at least somewhat important for 35%. Less than 6% consider travel costs unimportant or rather unimportant.

STRUCUTRAL EQUATION MODELING

The methodology of structural equation modeling is too complex to be fully presented in a paper. For this reason, an overview of SEM is first given below, followed by a practical application based on the data obtained in the aforementioned survey. For more in-depth information, there are a number of publications from different disciplines that deal extensively with the methodology and possible applications in various subject areas (*5, 6*).

Theory

One of the greatest challenges in science is to identify dependencies of different influencing factors on each other, especially when these cannot be measured directly, i.e. are latent, and the number of variables increases. Over the last decades, several methods have been developed by a variety of researchers in different disciplines to make these hidden dependencies quantifiable. In the process, different methods have been established in different branches of research. In social sciences, humanities, and economics, structural equation modeling (SEM) plays a significant role, while in engineering and transportation sciences it can play only a minor role or not be involved at all. The central concern of SEM is the representation of causal dependencies and cause-effect relationships (*7–9*).

To place it in the scientific environment, SEM can be described as a statistical method that contains elements of factor analysis and path analysis (*10*). These are established methods and have been used for over 100 years. Factor analysis was developed by Spearman, among others, at the beginning of the 20th century before being extended and refined by Thurstone and Jöreskog, among others, in the mid-20th century (*11*). It is used to draw conclusions about latent variables from measurable parameters. Path analysis is somewhat younger than structural analysis and goes back in particular to Wright, who in the middle of the 20th century was looking for a method to describe causal relationships. (*11*).

In part, Wright's path analyses are referred to in the literature as the first generation of structural equation models (*12*). This approach is however controversial (*11*). The second generation of SEM, which is also generally recognized as such, developed from the 1970s onwards by combining path analysis with factor analysis. From the 2000s, a third generation of SEM emerged, which includes Bayesian modeling and the "structural causal model". (*12, 13*)

A structural equation model usually consists of different submodels, the outer measurement models and the inner structural model.

The measurement models represent the relationships of the latent variables to each other. However, since latent variables are not directly measurable, suitable empirical measurement variables are assigned to them in order to capture the latent variables as accurately as possible. However, it is important when selecting the measurement variables that they allow valid conclusions to be drawn about the respective latent variable and that they are linked to it as directly as possible. One of the reasons for this is that measured variables are prone to error, and losses in accuracy can also occur when one or more measured variables are linked to a latent variable. In the present example, x and y represent the indicators for latent exogenous and endogenous variables. Residual terms (δ - measurement error / residual variable for an indicator x or ε - measurement error / residual variable for an indicator y) are used in the measurement model to describe the latent variables. (*7, 14*)

The structural models, in turn, depict the effective relationships between the exogenous and endogenous variables in the form of a path diagram. The starting point are the theories and hypotheses. Latent variables that explain other variables in the structural model are called exogenous (ξ) and those that are explained by exogenous latent variables are called endogenous (η). (*7, 14*)

For illustration, a generalized structural equation model is shown in Figure 8. The SEM shown consists of a total of two exogenous constructs $\xi 1$ and $\xi 2$ and one endogenous construct $\eta 1$. The hypothesized relationships between the latent constructs are shown by arrows in a path diagram, denoted as path coefficients (γ). (*7*)

In the present example, π and λ represent the path coefficients for latent respective exogenous and endogenous variables.

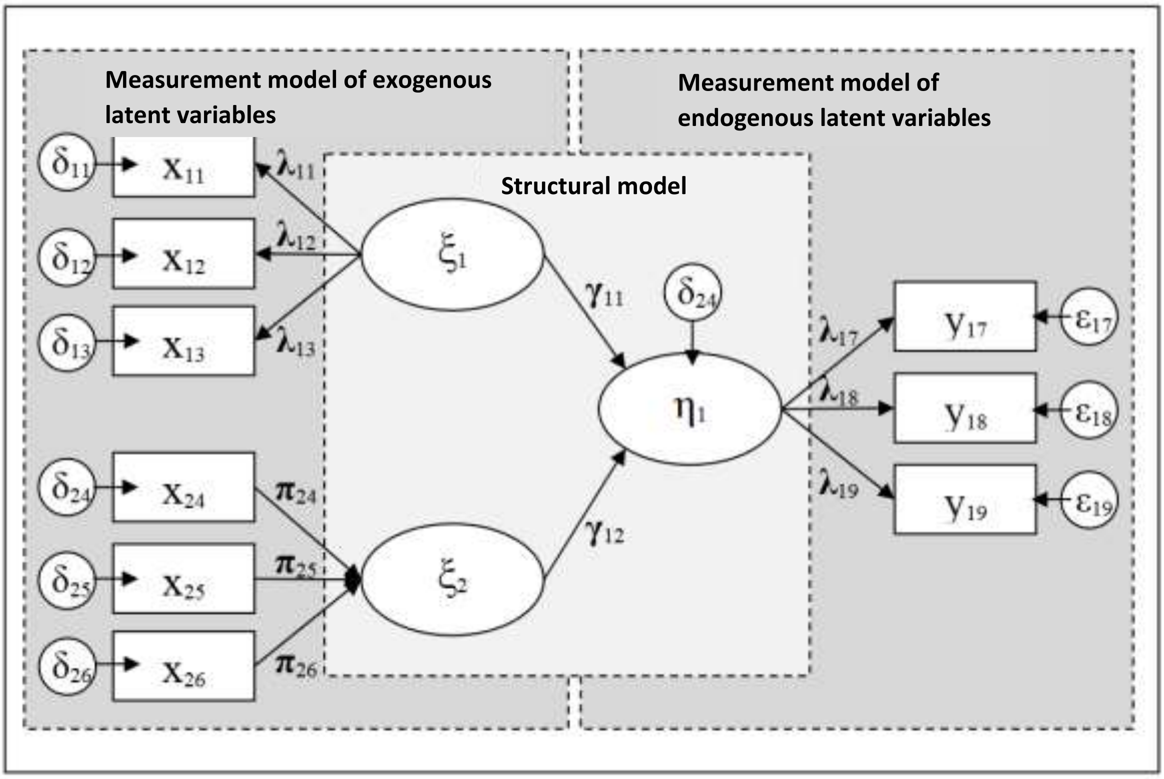

Figure 8: Structure of a complete SEM according to (7)

The coefficients used may vary depending on the initial model, but the general structure is common to all models. In the present case, the authors have based their notation on the models of Jöreskog and Sörbom. (*15*).

There are different approaches about the process of structural equation modeling. In (*14*) the following general approach is proposed, the individual steps of which are explained below:

- Classification of the latent variables according to endogenous and exogenous variables
- Creation of the structural model (formulation of hypotheses for each endogenous variable)
- Formulation of the measurement models for each latent variable
- Graphical illustration of the causal model (path diagram creation)
- Conversion of the path diagram into a linear system of equations
- Estimation of the system of equations path coefficients
    - Analysis of covariance approach
    - Variance analytical approach

The processing of a structural equation model begins with assigning the respective latent variables to the established hypotheses, which are then assigned the endogenous and exogenous measured variables necessary for their determination. The structural model, which visualizes the presumed causal relationships, is then constructed from the hypotheses established above. Whether exogenous or endogenous variables are present is quickly apparent here, since only arrows emanate from exogenous variables. In the case of endogenous variables at least one arrowhead points to the variable. Since latent variables by their nature cannot be measured directly, the measurement models for the respective latent variables are determined in the third step. Two types of measurement models are distinguished. Formative measurement models are given if the observable indicators directly cause the latent variable, which corresponds to the latent variable ξ_2 in Figure 8. In contrast, there are reflective measurement models, as shown in Figure 8 of latent variable ξ_1, where the observable variables are affected by the latent variable. The central question in this step is therefore whether the change in the measured variable causes a change in the latent variable or whether the change in the latent variable causes a change in the measured variable. This already takes up the fourth step, the creation of the path diagram. The structural equation model can be created relatively easily from the combination of the measurement models and structural models. The structure always follows the same scheme. The structural model is shown in the center, the measurement model of the latent exogenous variables is to the left of it, and the measurement model of the latent endogenous variables is to the right of it. In addition, there are specifications regarding the presentation, but for these we refer here to the literature, for example (*14*) and (*16*). To test the formulated hypotheses, in the fifth step of SEM the models must be translated into systems of equations. Help is provided here by the set up path diagram to easily identify the relationships. An equation is set up for each dependent variable. These equations are then combined into matrices. The last step is the estimation of the equation system for its (approximate) solution. Two approaches are distinguished for this, each with different advantages and disadvantages depending on the hypothesis system. The covariance analysis approach tries to draw conclusions about dependency relationships with the help of variances and covariances of observable variables. In contrast, the variance-analytic approach tries to achieve the most exact predictions of the actual observed values by means of the least squares method. (*7–9, 12, 14, 16, 17*)

Another approach to setting up structural equation modeling, which the authors of this paper have largely followed, is presented in (7).

- Theoretical foundation and hypothesis generation
- Choice of method
- Model formulation
- Empirical survey
- Parameter estimation
- Evaluation of the estimation results
- Modification of the model structure

Most of the steps are the same in content as in the model mentioned before, but here, for example, an optimization loop is included. A more detailed description of the individual steps is omitted in the following and reference is made to the sources and secondary literature (*7*).

Discussion of SEM

In other scientific fields, such as economics or psychology, there is already extensive experience with structural equation modeling and evaluations of the strengths and weaknesses of the method. One of the greatest advantages is the ability to determine latent variables and to measure the dependencies and their strength between individual variables. The individual variables can also have complex relationships to each other. In addition, complex relationships can be represented clearly and quickly in a structural equation model. By choosing appropriate factors, measurement errors in the system can be minimized. SEM quickly shows whether the developed hypotheses are correct or whether variables have an influence on the overall system. Assumptions are relatively easy to model and test in an existing model; moreover, optimizations are a standard part of many programs. (*18, 19*)

Critical about structural equation models is their complexity in calculating and determining the variables. For most users, the available programs represent a black box, which delivers results based on input data, but which are difficult to verify. One of the greatest challenges, however, is the translation of the developed hypotheses into functioning models. The amount of data available must exceed a significance threshold, otherwise there is a risk of falsified results. (*18, 19*)

Modeling

Furthermore, we used structural equation modeling with SmartPLS 3.0 to evaluate the factors influencing the model choice as a complete model. Also, the model gives a good survey of the variable dependencies. It is shown in Figure 9.

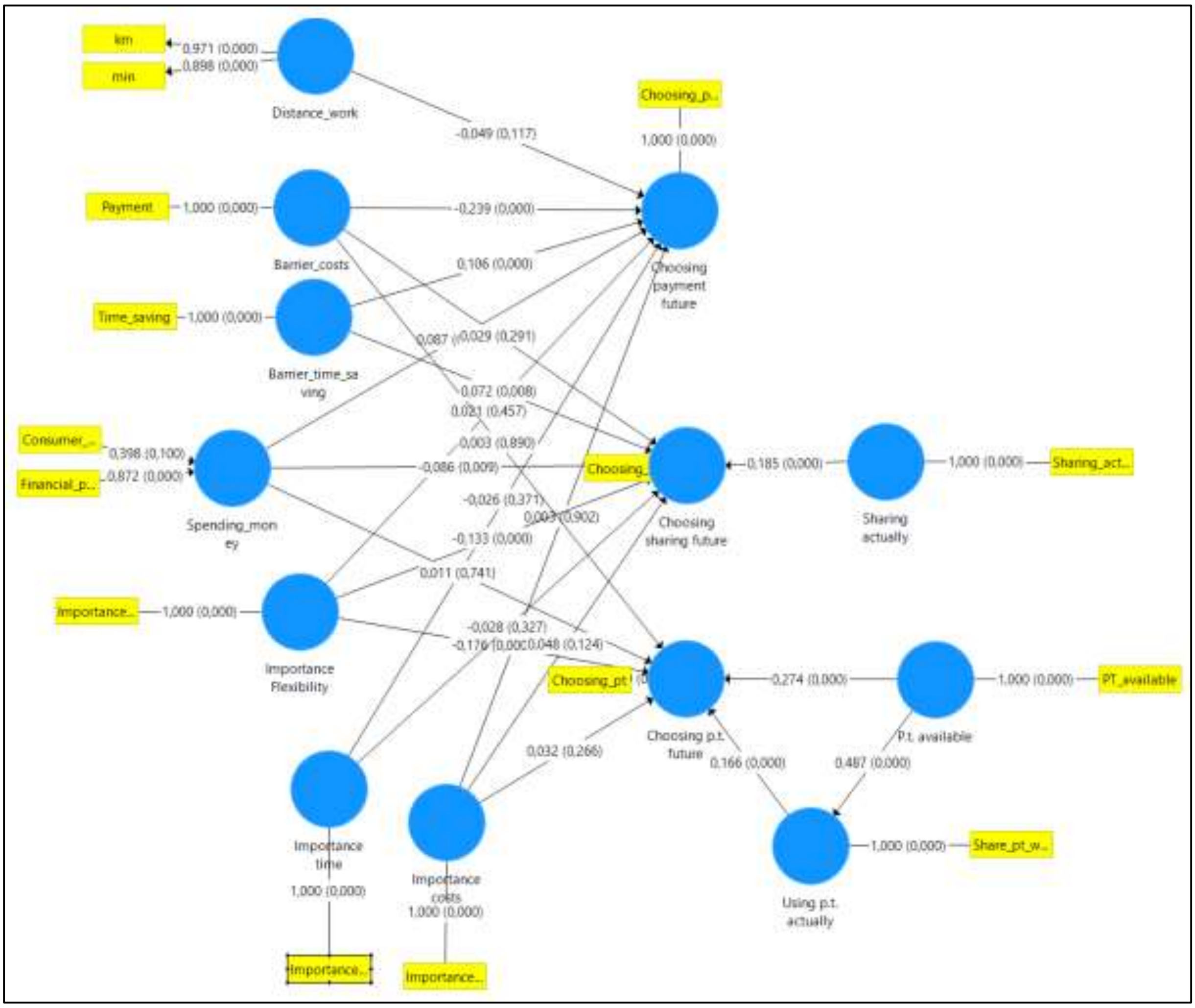

Figure 9: Structural equation model of the factors influencing the modal choice. The numbers indicate the weights and the p-values (in brackets).

It can be seen that the choice for using a paid express lane is impacted by the price of the lane (p<0.01), the saved time (p<0.01) and the possibility and willingness to spend money in general (p=0.019). In contrast, the choice is not impacted by the distance to work (p=0.17), the wish for flexibility (p=0.457), the personal importance of time (p=0.371) and the personal importance of costs (p=0.902).

The choice for car sharing in the scenarios is impacted the saved time (p=0.008), the possibility and willingness to spend money in general (p= 0.009), (negatively) by the wish for flexibility (p<0.001) and of course by the current usage of car sharing (p<0.01). In contrast, it is not impacted by the express lane costs (p=0.291), the personal importance of time (p=0.341) and the personal importance of costs (p=0.124).

The choice for the usage of public transport is (negatively) impacted by the wish for flexibility (p<0.001), the availability of public transport (p<0.01) and the actual usage of public transport, which is itself also impacted by the availability. In contrast, the choice for the usage of public transport is not impacted by the express lane costs (p=0.890), the possibility and willingness to spend money in general (p= 0.741) and the personal importance of costs (p=0.266).

Further connections between the variables which are not shown in Figure 9 didn't show an impact.

INTERPRETATION

In the past decades, transport planners in Germany have mainly reacted to capacity bottlenecks and changing demand by building new roads and expanding existing ones. In recent years, however, there has been a change in thinking here. Especially in the vicinity of metropolitan areas, many stakeholders are now competing for limited available space, , making new major construction and expansion projects more difficult. A change in the population's environmental awareness and strained public finances are also playing a significant role in the emerging changes. Managed lanes, such as HOV lanes or HOT lanes, which are not currently used in Germany, can contribute to solving the problem. Against this background, the Technical University of Munich conducted a survey in the first half of 2022 to find out what commuters value on their way to work and where they are potentially prepared to accept cutbacks.

The results show that both the HOV lane and the HOT lane have considerable potential in Germany. It is true that only 18% of respondents currently use carpooling at least occasionally, and the number of those who use carpooling several times a week is even lower. However, around 90% of respondents would consider carpooling at least occasionally in the future and, depending on the scenario, 75% - 80% of respondents also chose carpooling at least for occasional trips in the scenarios. However, these figures also depend on commuters' expectations. Only about 40% of respondents would consider carpooling without monetary or time incentives, while for 50% this would be a prerequisite. This is where the opportunity lies for HOV lanes to generate travel time gains on highly congested long-distance roads in urban environments that compensate for losses in flexibility and convenience. However, to achieve the desired effect, the respective route must be of sufficient length and have a certain level of congestion, since, for example, a distance of about 10 km must be covered to obtain a travel time advantage of 5 minutes at a speed difference of 40 km/h and a speed of 50 km/h in the general-purpose lane. In order to create incentives and to decrease the number of those who cannot imagine carpooling or only carpool occasionally, it would be necessary to implement a successful pilot project in Germany.

Since HOV lanes with low utilization waste valuable capacities and also cause problems in acceptance among the population, the authors follow the international trend towards HOT lanes (*20*) and fill free capacities of managed lanes with paying commuters. It was found that willingness to pay is strongly dependent on price and the potential travel time gains, so that the level of the user fee is well suited as a control instrument. However, practical experience at the Fast lane in Tel Aviv in recent years also showed that willingness to pay increases significantly when commuters experience that the investment is subjectively worthwhile for them (*21*). Based on the survey data, psychological thresholds appear to be €5 and €10 cost per trip, but this was not investigated in sufficient depth and needs to be the subject of further work.

In general, the data suggest that commuting behavior in Germany is becoming more flexible. Whereas it used to be common to drive to work in the same way every day, for the different scenarios, survey participants indicate that they resort to different elements such as carpooling or paid express lanes. This correlates with the number of days when important appointments are scheduled in the morning and arriving on time is an important consideration. In general, however, the work environment is becoming more flexible, leading to the acceptance of longer or less flexible alternatives for commuting if the overall financial, time, or socioeconomic benefits outweigh the disadvantages.

In the context of this paper, the data obtained were analyzed using structural equation modeling in addition to classical methods. This method has been used to a greater extent in other research fields, such as economics, psychology, or social sciences and humanities, but hardly ever in the context of transportation science. Especially for experienced users, the central statements of the investigation can be read off from the models in a short time on the one hand and presented on the other hand. In addition, dependencies that cannot be measured directly can be determined and represented. This is seen as a major strength of SEM across disciplines (*22*). In the present study, for example, it can be shown that willingness to spend money and the user fees of a managed lane have no influence on whether a person uses public transport. This means that the introduction of road user charges is not expected to have any shifting effects on existing public transport services. Only new services and associated capacity increases would cause a shift in choice decisions.

CONCLUSION

Our take-home-message could be summarized as follows: There is great potential.

Both the tested procedure of structural equation modeling and the data obtained from the survey show that more in-depth investigations or a follow-up are worthwhile here. Using SEM, it was possible to visualize the hidden dependencies of the variables in the survey and measure their strength. The path diagram created facilitated both the formulation of the hypotheses and their evaluation and presentation of the results. In the next step, the authors will also examine and process larger data sets using SEM. In individual cases it must be examined whether adaptations have to be made to the approaches of colleagues from other research fields such as economics or psychology in order to make SEM even more effective for transportation science. In any case, the existing literature as well as the relevant software provides a good starting point. Dabei spielen auch die in der Diskussion der SEM genannten Stärken und Schwächen eine zentrale Rolle. Nevertheless, we see the SEM as a tool for future studies, for example when it comes to the potential of new forms of mobility.

The survey data also show the potential for managed lanes that lies dormant in Germany and now needs to be harnessed in the context of rapidly changing mobility. There is a surprisingly high willingness to carpool as well as to pay user fees for special use lanes. This is good news since that new road construction has largely come to a standstill and the expansion of existing lanes has been severely limited. Managed lanes, especially HOV and HOT lanes, offer great potential for improving traffic flow. Here, politicians, administrators, transport providers and the private sector are now called upon to work together to create holistic approaches for sustainable traffic. This includes improving the framework conditions for carpooling, for example in the form of commuter parking spaces or exclusive parking facilities at workplaces, as well as creating the legal and planning conditions for pilot projects. Demand-oriented public transportation services must be coordinated with the areas area development at both the starting point and the destination to supplement the range of services. If this succeeds, at least some bottlenecks can be diffused and the safety and ease of traffic can be improved. The authors will develop proposals for measures in follow-up projects and evaluate their effects in the route network. Various projects, for example in the USA or Israel, can serve as a model here, as their experience, some of which spans decades, is a valuable resource for future planning. It is always important to keep an eye on local conditions, however. Past experience has regularly shown that a 1:1 transfer of successful projects is not possible.

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Author contributions

The authors confirm contribution to the paper as follows: study conception and design: Th. Schoenhofer, B. Kaltenhaeuser, K. Bogenberger; data collection, analysis and interpretation of results: Th. Schoenhofer, B. Kaltenhaeuser; draft manuscript preparation: Th. Schoenhofer, B. Kaltenhaeuser, K. Bogenberger. All authors reviewed the results and approved the final version of the manuscript.

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