ANALYSIS OF THE EFFECTS OF AN HOV LANE ON A GERMAN FREEWAY – A SIMULATION STUDY WITH PTV VISSIM

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ABSTRACT

The objective of our research is to assess the effects of a high occupancy vehicle (HOV) lane on a German federal freeway. The research findings provide guidance for practitioners for the development of a microscopic traffic flow model containing temporary hard shoulder running and an HOV lane in PTV Vissim.

We developed a microscopic traffic flow model of a section of a German freeway. The driving behavior was calibrated with measured traffic data of the existing dynamic line control system. We used this model to simulate 16 scenarios of an HOV lane (four HOV lane designs combined with four vehicle occupancies).

The results showed the desired effects of an HOV lane can only be achieved to a small extent. The reduction of general purpose lane capacity is too high when introducing an HOV lane. Furthermore, the introduction of an HOV lane results in additional lane changes in the upstream area from the HOV lane in the simulation. The reduced capacity in combination with increased lane changes leads to congestion, both for HOVs and SOVs. Only on the section of the HOV lane itself, HOVs are faster than SOVs. Downstream the traffic situation remains the same as in the baseline scenario. Therefore, the potential for travel time savings for HOVs compared to SOVs is low.

One of four HOV lane designs offers 4 minutes travel time savings for HOVs over SOVs. It is questionable whether a minor time gain is enough to change people's mobility behavior towards carpooling.

INTRODUCTION

Traffic problems caused by congested roads are generally solved by increasing the capacity of the existing infrastructure. However, an expansion of the transport infrastructure will induce new traffic, and the problems are recurring over time. In terms of a sustainable transport policy, the existing infrastructure should be used more efficiently instead of building new infrastructure. (*1*)

An increase in vehicle occupancy could help in this case. High occupancy vehicle lanes (HOV lanes) are an approach used in many countries, especially in the United States, to promote carpooling, thus reducing traffic and relieving the traffic network. HOV lanes can exclusively be used by vehicles with a minimum number of occupants. Incentives for the formation of carpools are above all travel time savings (*2*). By restricting a general purpose lane to an HOV lane, traffic congestion on the remaining general purpose lanes will become worse as long as the utilization of the HOV lane is low. Only when the benefits of using the HOV lane motivates the formation of additional carpools, the overall traffic volume will be reduced, and the situation of all road users will improve (*3*).

In Germany, the HOV facilities have not been used so far, and there is little research in this area. So the question arises whether there is a potential for HOV lanes on German federal freeways. Our study was motivated by the transport department of the federal state of Baden-Württemberg asking the following questions: How could HOV lanes be integrated in the design of German freeways and what effects will they have on traffic flow? Which vehicle occupancy is required to generate travel time savings for all drivers?

Our approach to answer these questions is using microscopic traffic flow simulation. In our paper, we describe the modeling process for a German freeway including a dynamic line control system and temporary hard shoulder running as well as the modeling HOV lanes and their usage.

The basis for the study is a microscopic traffic model of a section of freeway no. 8 in the area of the city Stuttgart. Among other things, this section offers good preconditions for the introduction of an HOV lane due to the equipment with temporary hard shoulder running and the existence of a four-lane section, what is the exception in Germany. The study does not look at the effects of offering HOV lanes on the formation of carpools but is limited on the traffic engineering related aspects.

In the following, a literature review will provide insight into the experiences made with HOV lanes with a focus on European implementations. Furthermore, existing research on the simulation of HOV lanes is reviewed. The traffic data used and the development of the microscopic traffic flow model will be described subsequently.

In the next step, the modeling of 16 scenarios (four HOV lane designs with four different vehicle occupancies) in PTV Vissim is described. Finally, the speeds and the travel times with and without an HOV lane are evaluated for each scenario. We assume in the following descriptions that the reader is familiar with the handling of Vissim. The simulations were carried out with Vissim version 10.00-09.

LITERATURE REVIEW

HOV facilities have their origin in the United States and are still a central element of traffic demand management in North American cities (*4–6*). In the US, the total length of HOV lanes in operation has doubled from 1500 miles to more than 3000 miles between 1995 and 2005 (*7*). The Federal Highway Administration released the last inventory of HOV lanes in 2008. At this time, there were 301 HOV facilities in operation. (*8*) The travel time savings due to HOV lanes varied widely depending on the location and were between 0.4 and 37 minutes (*9*). Literature does not contain any information on the relation between the length of the respective HOV lanes and travel time savings.

In Europe, HOV lanes are currently used in only a few locations. The reason is that in most European cities public transport is well developed, and there are much fewer high-performance urban freeways than in the US (*10*). However, some European cities have introduced HOV lanes on freeways or main urban roads in the 1990s and early 2000s.

In Great Britain, one HOV lane was opened in Leeds (*11*) and one in Bristol (*12*). In Leeds, the average occupancy of vehicles increased from 1.35 to 1.41 passengers per vehicle in the first two years, the travel time savings for HOVs were about 3.5 minutes for a five-kilometer journey (*13*). In Bristol, the share of HOVs climbed from 20% to 27% (*12*). In the Netherlands, a barrier-separated HOV lane was opened on a freeway near Amsterdam (*6, 14*). For legal reasons, it had to be released for general traffic one year later (*15*). In Norway, one HOV lane was introduced in Trondheim and one in Kristiansand (*16*). In Trondheim, vehicle occupancy climbed from 1.33 to 1.37 passengers per vehicle, the average travel time saving was 35 seconds for an HOV (*16*). In Kristiansand, vehicle occupancy increased from 1.20 to 1.27 passengers per vehicle in the morning peak period after one year (*16*). In Austria, an existing bus lane was opened for HOVs in Linz (*6, 14*). There were no changes in vehicle occupancy observed, although the maximum travel time saving for HOVs was 24 minutes during rush hour (*17*). In Spain, a barrier-separated HOV lane opened on a freeway in Madrid. Public transport lines also use this HOV lane. Maximum travel time savings for HOVs were 15 minutes and the vehicle occupancy increased from 1.75 to 2.03 passengers per vehicle between 1991 and 2001 (including busses) (*1, 6, 14*). All major investigations were carried out shortly after the introduction of the HOV lanes. Since there are no recent publications on these HOV lanes, the long-term effects and benefits cannot be assessed.

In most mentioned cities, the average occupancy of vehicles could only be increased marginally and the travel time did not decrease significantly. Since the early 2000s, no HOV lanes have been introduced in European cities.

Due to increasing traffic volumes and growing bottlenecks in the transport network, the idea of favoring carpools to reduce traffic is becoming popular again. On the Belgian freeway E411, the hard shoulder will be opened for carpools with at least three passengers per vehicle by the end of 2018 in order to cope with commuter flows in the border region between Belgium and Luxembourg (*18, 19*). This project has been made public in the Belgian and Luxembourgish press, but so far there is no information about scientific monitoring.

Before implementing an HOV lane, the expected effects are often analyzed using microsimulation. Gomes et al. (*20*) describe the construction and calibration process of a traffic flow model in Vissim for a Californian freeway containing an HOV lane. Dynamic traffic assignment is used as a modeling approach. Separate link costs are assigned to HOVs and single occupancy vehicles (SOVs) making the HOV lane favorable for HOVs. As SOVs are not allowed to use the HOV lane, it is blocked for SOVs. The routing decision in this model consists of HOVs choosing to enter the HOV lane or to stay on the general purpose lanes. A single iteration of the dynamic traffic assignment is sufficient, as only the link costs and not the travel times are considered for the assignment.

Fontes et al. (*21*) investigated the effects of an HOV lane in a medium-sized European city using Vissim. Their baseline scenario assumes an average vehicle occupancy of 1.37 passengers per vehicle, in further scenarios an increase to 1.50 and 1.70 passengers per vehicle is defined. The results show that travel time savings of 2.4% can be achieved with a vehicle occupancy of 1.70 passengers per vehicle. For the baseline scenario, the introduction of an HOV lane results in an increase of the travel times. The approach for modeling an HOV lane is not described.

Sajjadi and Kondyli (*22*) perform a calibration of two high occupancy toll (HOT) segments in South Florida using Vissim. In this study only managed lanes are modeled in Vissim, general purpose lanes are not replicated. The approach for modeling a HOT lane is not described.

DATA AND TRAFFIC MODEL

Examined Freeway Section

The basis for the study is a traffic model of a section of freeway no. 8 near Stuttgart. Freeway no. 8 is an important east-west connection in southern Germany and connects Karlsruhe to Munich via Stuttgart. The modeled section is located near the city of Stuttgart, a significant economic hub in Germany and Europe. Accordingly, traffic volumes are very high on this section and congestions occur regularly on the freeway, especially during peak hours.

The model represents traffic conditions in the morning peak period between the intersections *Leonberg-West* (no. 48) and *Stuttgart-Degerloch* (no. 52b). To capture effects from upstream metering or downstream congestion, the model was extended in the direction of travel Munich along six intersections. Figure 1 shows the section with all its characteristics. The freeway mainline of this section is composed of three lanes (per direction of travel). Between intersections no. 50 and no. 51 the mainline is extended to four lanes.

The roadway geometry is replicated in Vissim based on aerial images of the section. The general purpose lanes, hard shoulder, and ramps in the intersections are modeled.

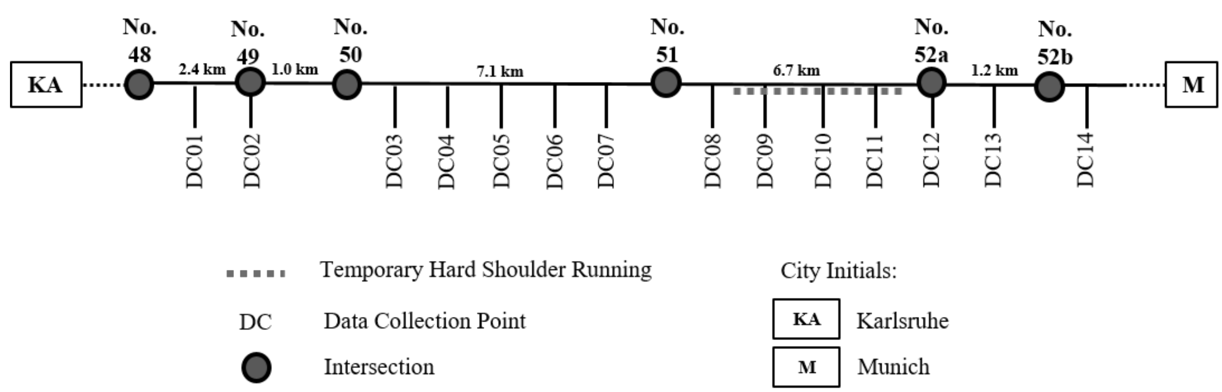


FIGURE 1 : Investigated Freeway Section

Average Vehicle Occupancy and Investigation Period

In Germany, the average occupancy for commuting is 1.2 passengers per vehicle, the lowest for all trip purposes. The average occupancy of vehicles for all trip purposes is 1.5 passengers per vehicle. An analysis of the departure times depending on trip purpose has shown that trips in the morning involve almost exclusively commuting. In the afternoon, there are more leisure and shopping trips besides commuting. (*23*) As the potential for a change in mobility behavior is highest during the morning peak period, this period is chosen for the study. For the current situation, traffic statistics (*23*) report a share of 86,7% single occupancy vehicles (SOV) and 13,3% high occupancy vehicles with two or more occupants (HOV).

For the investigation, the morning peak period in traffic is defined between 6:00 and 11:00 am. The simulation requires an additional warm-up period. Therefore, all traffic data is processed from 5:00 to 11:00 am and fed into the traffic model.

Traffic data of a two-week period is analyzed with regard to traffic flow and speed as well as weather conditions. The analysis revealed a typical day that reflects well the traffic problems of the investigated section well and therefore offers good preconditions for the modeling of the network.

Traffic Data

The investigated freeway section presented in figure 1 is equipped with a dynamic line control system, which includes 14 data collection points provided with traffic detectors and variable traffic sign gantries.

Temporary hard shoulder running is installed over a length of 4.3 kilometers between intersections no. 51 and 52a. If traffic sensors report a capacity bottleneck, the hard shoulder will be released for traffic for a limited period of time to improve the traffic flow.

The collected traffic data of the examined section is required both for determining the vehicle inputs in Vissim and for calibration. Radar detectors provide traffic volume and average speed separately for cars and trucks for each data collection point. Traffic data is aggregated to one-minute intervals. In addition, the vehicle input to the freeway is available for the intersections and includes traffic volume and average speed separately for cars and trucks.

Vehicle Compositions and Routes

The vehicle composition is split into cars and trucks. Cars are composed of SOVs (vehicles with only one occupant) and HOVs (vehicles with several occupants). In Vissim, the three vehicle types *HOV*, *SOV*, and *truck* are created and assigned to the corresponding vehicle classes. The provided traffic data contains information about truck and car shares. HOV and SOV shares are derived from assumptions about the average occupancy of vehicles in Germany as explained above.

For each on-ramp two vehicle inputs are created, one for car input and one for truck input. The corresponding vehicle compositions are assigned to the car and truck inputs. According to the assumptions for the vehicle occupancy in the morning peak period, the vehicle composition of the car input consists of 86.7% SOVs and 13.3% HOVs in the baseline scenario. The HOV and SOV shares vary in the following scenarios depending on the average vehicle occupancy. Traffic inputs are calculated in five-minute intervals between 5:00 and 11:00 am based on the real traffic data.

As there is no measured data on vehicle routes for the investigated section, PTV Validate, a traffic demand model for Germany, was used to derive origin-destination-flows. Validate includes car and truck volumes as well as a traffic assignment, calculated in PTV VISUM, which provides the drivers' route choices. (*24*)

Validate contains traffic demand separately for cars and trucks in one-hour intervals for a typical working day (Tuesday, Wednesday or Thursday). A traffic assignment provides the route choices for the entire German major highway network.

The resulting OD-matrices for cars and trucks are implemented into Vissim. For this purpose, two static vehicle routing decisions are created for each on-ramp, one for cars (SOVs and HOVs) and one for trucks. For each routing decision, static vehicle routes to all subsequent off-ramps are created.

Line Control System Modeling

Each data collection point on the investigated section (see figure 1) is provided with a dynamic traffic sign gantry, which displays traffic signs to the drivers based on the traffic situation. To ensure comparability between the actual state and the scenarios with HOV lane, the line control system is modeled statically. The variable speed limits, overtaking prohibition for trucks and hard shoulder opening and closing are time-dependent in the model and not traffic-actuated as in reality.

The speed limits prescribed by the dynamic line control system are modeled in Vissim by applying desired speed decisions on each data collection point. When in reality the variable traffic signs display a change of speed limit, the desired speed decision is adjusted in Vissim. These desired speed decisions contain different speed distributions for different vehicle classes.

The overtaking prohibition for trucks is modeled by blocking the passing lanes for the vehicle class *truck*.

The temporary hard shoulder running is installed over a length of 4.3 kilometers between intersections no. 51 and 52a. The number of lanes decreases from five to four and then to three general purpose lanes downstream from intersection no. 51. If the hard shoulder is released for traffic, vehicles can drive on four lanes in the usually three-lane section. Upstream from intersection no. 52a the three general purpose lanes are extended to five lanes in the intersection area (see figure 2 - lane configuration).

To model the temporary hard shoulder running in Vissim, the link between intersections no. 51 and 52a is split at the three data collection points of the line control system (DC09 – DC11) as well as at the beginning and end of the hard shoulder. Two connectors are inserted in each splitting point. One connector joins the three general purpose lanes; the second connector joins all four lanes (three general purpose lanes plus hard shoulder). Figure 2 shows the approach to model temporary hard shoulder running in Vissim used for the study.

For every section between two splitting points (sections 1, 2, 3, 4a and 4b), a *partial routing decision* is created, which includes one *partial route* (a) across the connector that joins the three general purpose lanes and one *partial route* (b) across the connector that joins all four lanes. The relative traffic load of the two partial routes is changed depending on whether the temporary hard shoulder running is switched on or off. If the temporary hard shoulder running is switched off, the relative traffic load on the partial route (a) is set to 100%. 0% of the vehicles choose the other partial route (b). If the temporary hard shoulder running is switched on, vehicles can use the hard shoulder in addition to the general purpose lanes. Traffic data analysis shows that not all the car drivers accept the hard shoulder as a general purpose lane. Therefore, only 80% of the cars are willing to use the hard shoulder in the model, whereas trucks accept this measure 100%. The partial routing decisions are therefore created separately for trucks and cars (*HOV* and *SOV*). For trucks, the hard shoulder is released by setting the relative traffic load on the partial route (b) to 100%. 0% of the trucks choose the partial route (a) that excludes the hard shoulder. For cars, the relative traffic load on the partial route (b) is set to 80%, and 20% of the cars choose the partial route (a).

To prevent vehicles from using the hard shoulder when the temporary hard shoulder running is switched off, the distance at which a vehicle initiates necessary lane changes to reach a connector is set higher than the length of the section itself. As soon as the vehicles follow the partial route (a), they change to one of the three general purpose lanes connected to the connector they have to pass in order to follow their partial route (a). Therefore, they do not drive on the hard shoulder.

In the investigated period, the temporary hard shoulder running is switched on between 6:44

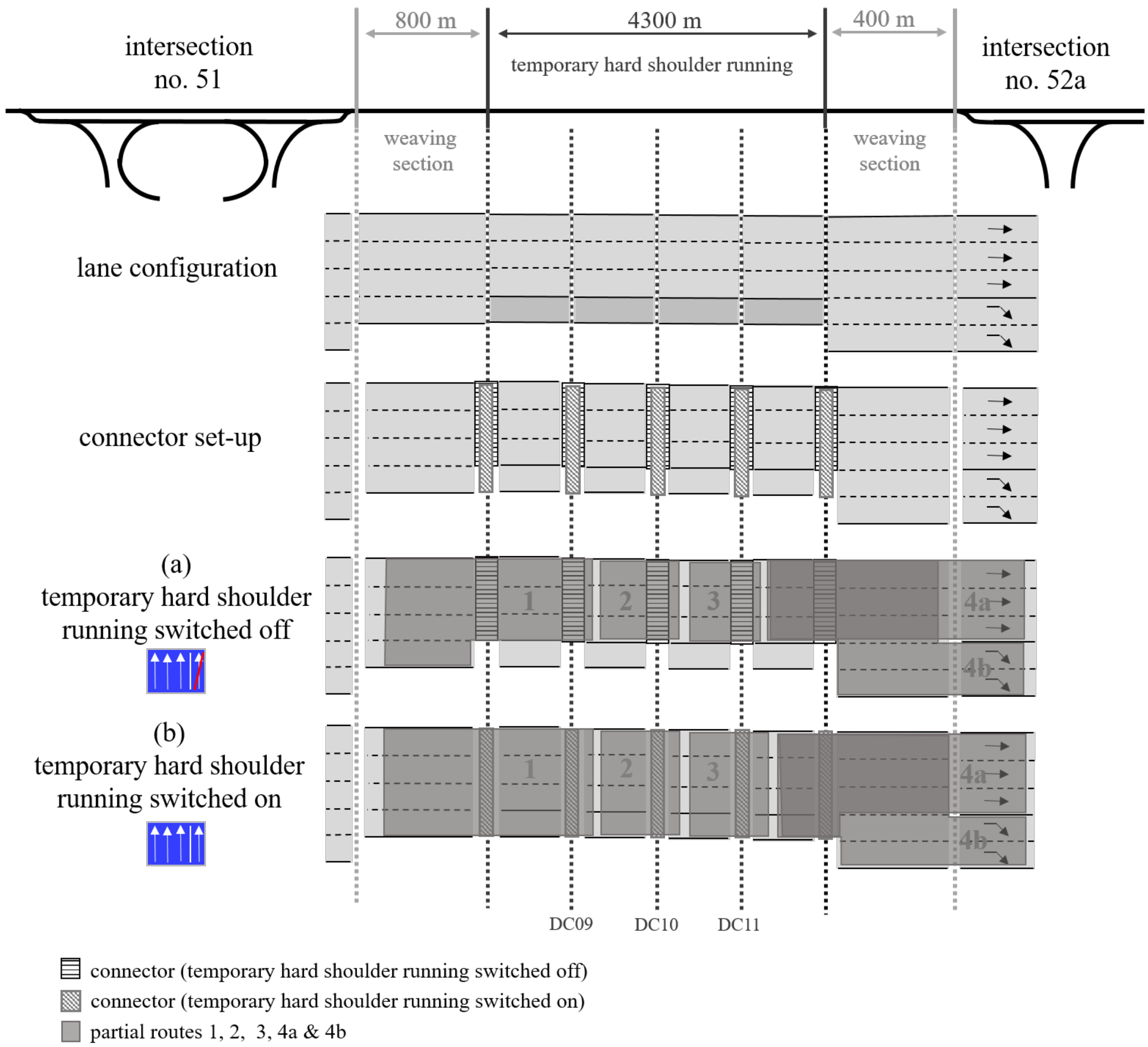


FIGURE 2 : Modeling Temporary Hard Shoulder Running in Vissim

and 8:40 am. The activation and deactivation of the temporary hard shoulder running in Vissim are executed via traffic-actuated programming (VAP), Vissim's built-in programming language for traffic-actuated control.

Calibration

Calibration is carried out manually based on the simulation model described above for the current situation without an HOV lane. During the calibration, 89 different parameter value modifications in the simulation are evaluated, each consisting of several simulation runs. The calibration is based on the actual traffic flow and speed at the data collection points.

Each modification in the simulation model is followed by several simulation runs to guarantee the reliability of the results. Traffic flows and speeds of the simulation runs are averaged for the evaluation. The goodness of fit is measured by the root mean square percentage errors (RMSPE).

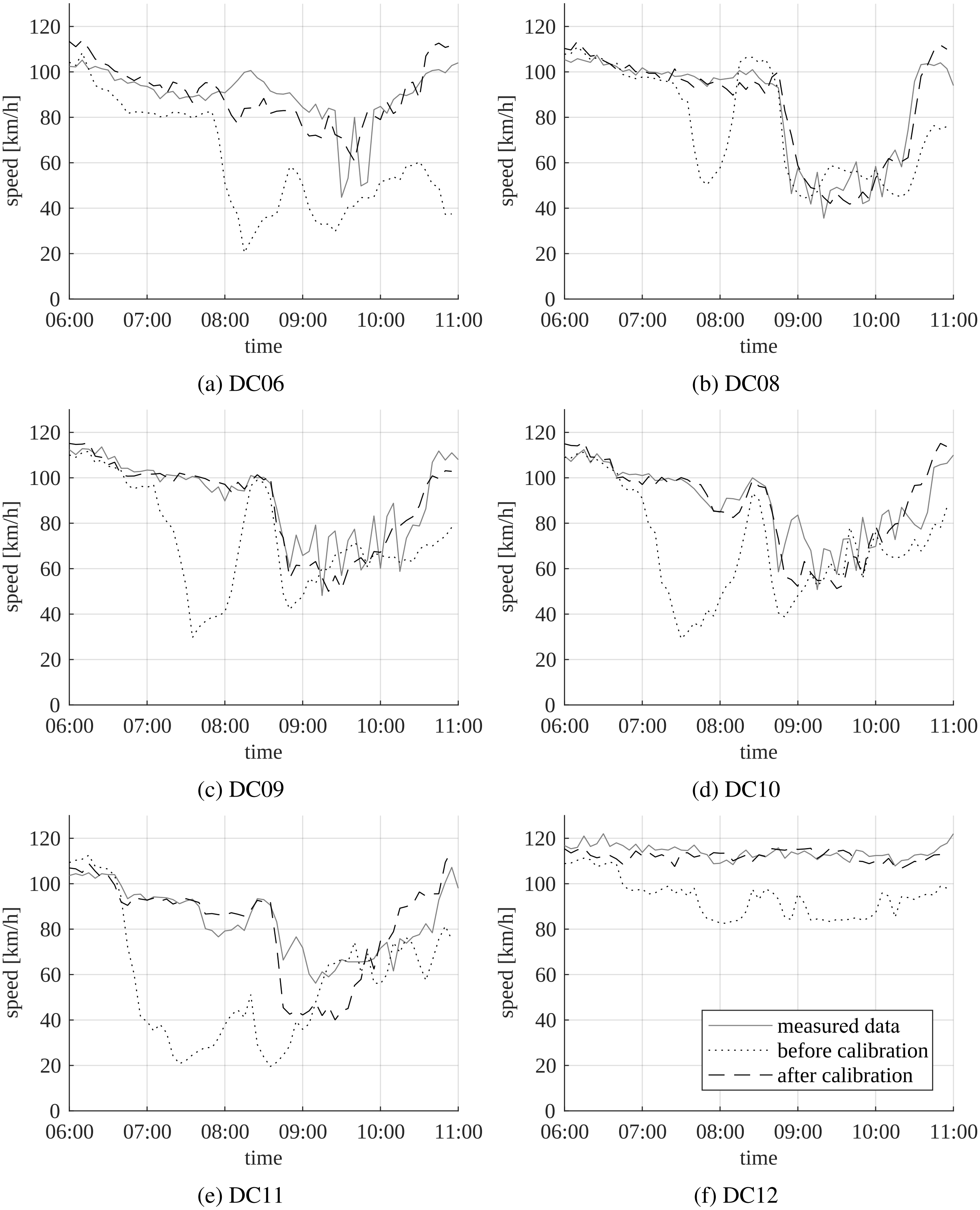


FIGURE 3 : Calibration Process - Speeds at 6 Data Collection Points

Figure 3 shows the results of the calibration process at six data collection points. DC06 and DC08 are located upstream from the section containing the temporary hard shoulder running, DC09 to DC11 are situated on that section and D12 is located downstream from it (see figure 1). The charts show real speeds compared to the speeds in the simulation before and after calibration.

The most important variables for calibration are the parameters of the driving behavior. For the traffic model of a freeway, both car following behavior and lane changing behavior are important. The car-following-model "*Wiedemann 99*" is chosen in Vissim. Wiedemann describes nine parameters, which can be adjusted to modify the car following behavior. The default parameters in Vissim do not result in realistic driving behavior for German freeways, so we used the parameter values developed by Geistefeldt et al. (*25*) and Leyn et al. (*26*) as the starting point for the calibration. To reproduce the specific conditions of our study area, further refinement was necessary.

Data collection point DC11 shows a highly congested traffic state. Due to the short weaving section upstream from intersection no. 52a, some vehicles do not manage to change lanes in time to reach their exit, and the consequence is the formation of traffic congestion. To realistically map the driving behavior, it is important to adjust the distance at which a vehicle first tries to initiate necessary lane changes correctly. On the modeled section, in the morning peak period, most drivers are commuters who are familiar with the freeway section and intersections. They know their route and make lane changes in time what can be reflected in Vissim by setting the parameters describing lane selection due to following a route. After calibration measured and simulated speeds at data collection point DC11 correspond well.

Before calibration, congestion starting at DC11 propagates to the upstream data collection points DC10 to DC06 in the simulation. After calibration, the simulated speeds correspond approximately to the measured speeds. It turns out that the speed level drops at about 8:40 am between data collection points DC08 and DC11, at this time the temporary hard shoulder running is closed.

Data collection point D12 shows that the vehicles are too slow in the simulation for free flow traffic conditions. Therefore, the default desired speed distributions were adjusted. There is no congestion propagating from DC12 to the temporary hard shoulder running section. Data collection points D13 and D14 show approximately the same speed profiles.

Furthermore, it proved helpful to use different values for the driving behavior parameters of cars and trucks, while in Vissim's default parameter sets these are the same.

In our study, the baseline scenario is the calibrated traffic flow model representing the current traffic situation on the modeled freeway section. This situation, without an HOV lane and with an average occupancy of vehicles of 1.2 passengers per vehicle, will be compared to the scenarios with an HOV lane.

SCENARIO DESCRIPTION AND MODELING

We investigated different designs of HOV lanes in combination with different vehicle occupancies and their effects on traffic flow and travel times with 16 scenarios. Figure 4 shows a simplified representation (not to scale) of the four designs of an HOV lane examined. All designs are conceived in such a way that no additional lanes have to be built.

For design 1, the effect of an HOV lane between intersections no. 50 and 51 is examined. This section is composed of four general purpose lanes while the left-most lane is converted to an HOV lane. For design 2, the HOV lane already starts in the intersection area of intersections no. 49

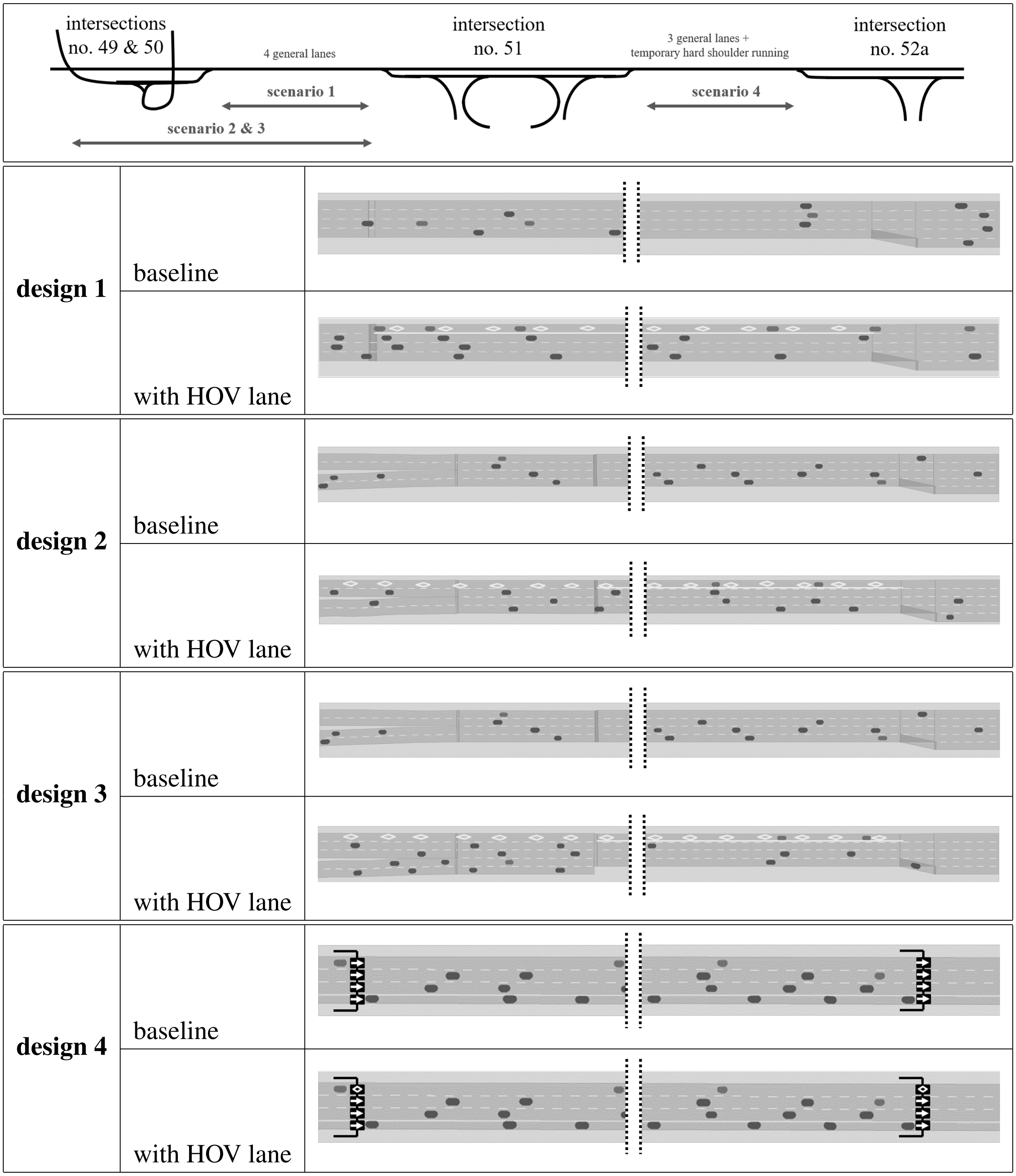


FIGURE 4 : Designs for the Introduction of an HOV Lane (Simplified Representation)

and 50, where the left one of the two general purpose lanes is turned into an HOV lane. Hence, within the intersection area, 50 % of the capacity of the mainline is restricted to HOVs. The HOV lane continues on the four-lane section, as it does in design 1 and ends in the weaving section of intersection no. 51. Design 3 corresponds to design 2, but additionally, the hard shoulder is released for general traffic within the intersection area to provide more capacity. Design 4 corresponds to a dynamic link between an HOV lane and the existing temporary hard shoulder running between intersections no. 51 and 52a. If the traffic volume reaches a certain threshold, the temporary hard shoulder running is opened, and the hard shoulder can be used in addition to the general purpose lanes. At the same time, the use of the left-most lane is restricted to carpools. Carpools are provided with the advantages of travel time savings, thus promoting carpooling and without giving single travelers the impression that capacity of the general purpose lanes is reduced. In peak periods, additional capacity is released for HOVs.

The aim of an HOV lane is to change people's mobility behavior. The idea is to create carpooling through the incentive of travel time savings. To supplement the scenarios we made assumptions about the change in vehicle occupancy. Initially, the different designs are examined with the current vehicle occupancy of 1.20 passengers per vehicle. Furthermore, the effect of an HOV lane is examined under the assumptions that the vehicle occupancy increases to 1.25, 1.30 and 1.35 passengers per vehicle. Additionally, it is assumed that the total number of passengers does not change. Therefore, an increase in the average occupancy leads to a reduction of the number of vehicles. Table 1 shows the modifications of vehicle compositions and traffic volumes depending on the vehicle occupancy.

The combination of the four HOV lane designs (1 - 4) with four average vehicle occupancies (a - d) leads to 16 investigation scenarios (1a - 4d).

TABLE 1 : Vehicle Composition Depending on Vehicle Occupancy

Vehicle Occupancy [Passengers/Vehicle]		**Vehicle Composition** **SOV** [%]	**HOV** [%]	**Traffic Volume** [%]
a	1,20	86,7	13,3	100 (reference value)
b	1,25	82,1	17,9	96,0
c	1,30	78,6	21,4	92,3
d	1,35	75,0	25,0	89,0

Acceptance of the measure and infringement rates are important aspects that significantly influence the success of an HOV lane. In our study, we assumed that the acceptance is encouraged with great care and violations are prevented. It is therefore expected that only 5 % of the HOVs refuse to use the HOV lane and 5 % of the SOVs use the HOV lane unauthorized.

The approach for modeling temporary hard shoulder running is applied to the modeling of an HOV lane (see figure 2). In Vissim, the section containing the HOV lane is equipped with different connectors, joining either the general purpose lanes or the HOV lane. *Partial routing* *decisions* are created, comprising different *partial routes* that are assigned to the vehicle classes *HOV*, *SOV* and *truck*. One partial route leads across the general purpose lanes. Single travelers and trucks are assigned to this partial route. A second partial route leads across the HOV lane and is assigned to HOVs (and unauthorized SOVs).

The distance at which a vehicle initiates necessary lane changes to reach a connector is set higher than the length of the HOV lane itself. Therefore, HOVs do not leave the HOV lane, and SOVs do not move to the HOV lane between the connectors.

SOVs have to leave the left-most lane upstream from the HOV lane. As HOVs have to perform up to three lane changes to reach the HOV lane, they do not have to access the HOV lane right at the starting point. However, HOVs try to enter the HOV lane as quickly as possible. Once the HOVs are on the HOV lane, they will only leave at the end of the HOV section.

There is no information on how the presence of an HOV lane affects the driving behavior. Therefore, we used the same driving behavior as in the baseline scenario.

RESULTS

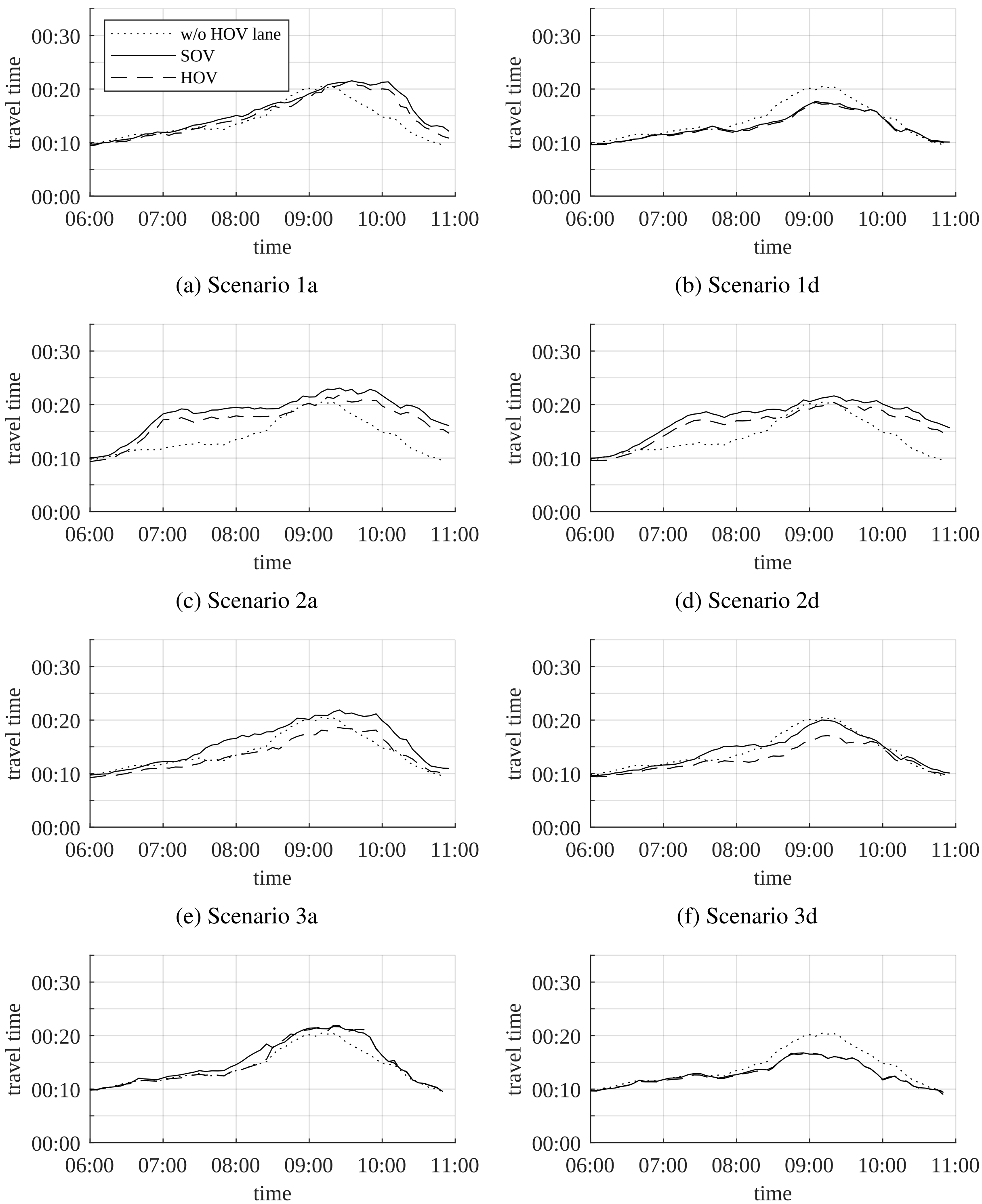
Figure 5 shows the travel times for a 19.5-kilometer journey between data collection points DC01 and DC14 separately for HOVs and SOVs. The travel times in the baseline scenario without HOV lane are compared to the scenarios with vehicle occupancies a and d (1.20 and 1.35 passengers per vehicle) for the four HOV lane designs. The travel times in the scenarios with vehicle occupancies b and c (1.25 and 1.30 passengers per vehicle) lie between the values for vehicle occupancies a and d and are not shown. For each scenario, we averaged and analyzed eight simulation runs. The different simulation runs have not produced any considerable variances in the results.

Figure 6 shows the mean speed difference in the scenarios compared to the baseline scenario at 14 data collection points separately for HOVs and SOVs.

With HOV lane design 1 we analyzed the effects of an HOV lane on a four-lane section. With the current vehicle occupancy of 1.20 passengers per vehicle (scenario 1a), travel times increase towards the end of the investigation period, both for HOVs and SOVs. HOVs have hardly any advantage over SOVs. The mean speed differences show higher speeds for HOVs on the HOV lane compared to SOVs and the baseline scenario. Upstream from the HOV lane, both HOVs and SOVs are slower than before the implementation of an HOV lane. Downstream there are almost no differences between HOVs and SOVs. An increase in vehicle occupancy results in travel time savings for all road users, without differences between HOVs and SOVs.

In the simulation, the HOV lane entails more lane changes. Without lane restrictions, the drivers' lane choices depend on their route, their desired speed and traffic conditions. By restricting a lane to HOVs, lane changes onto the HOV lane (by HOVs) and lane changes from the HOV lane to a general purpose lane (by SOVs) occur besides the regular lane changes. In the simulation, this leads to lower capacity, especially in the area upstream from the HOV lane and in peak periods, congestion occurs. Both, HOVs and SOVs, are slower than in the baseline scenario so that HOVs do not have travel time savings compared to SOVs. Only on the section of the HOV lane itself, HOVs are faster than SOVs. Downstream from the HOV lane, the traffic situation remains the same.

It is conceivable that the difference between European and American transport infrastructures is the reason for the problem of merging. In contrast to the US, driven speeds on German freeways are not homogeneous. In Germany, freeway speeds vary from slow on the right lane to fast on the left lane. The introduction of an HOV lane leads to a mixing of slow and fast vehicles,



(a) Scenario 1a

(b) Scenario 1d

(c) Scenario 2a

(d) Scenario 2d

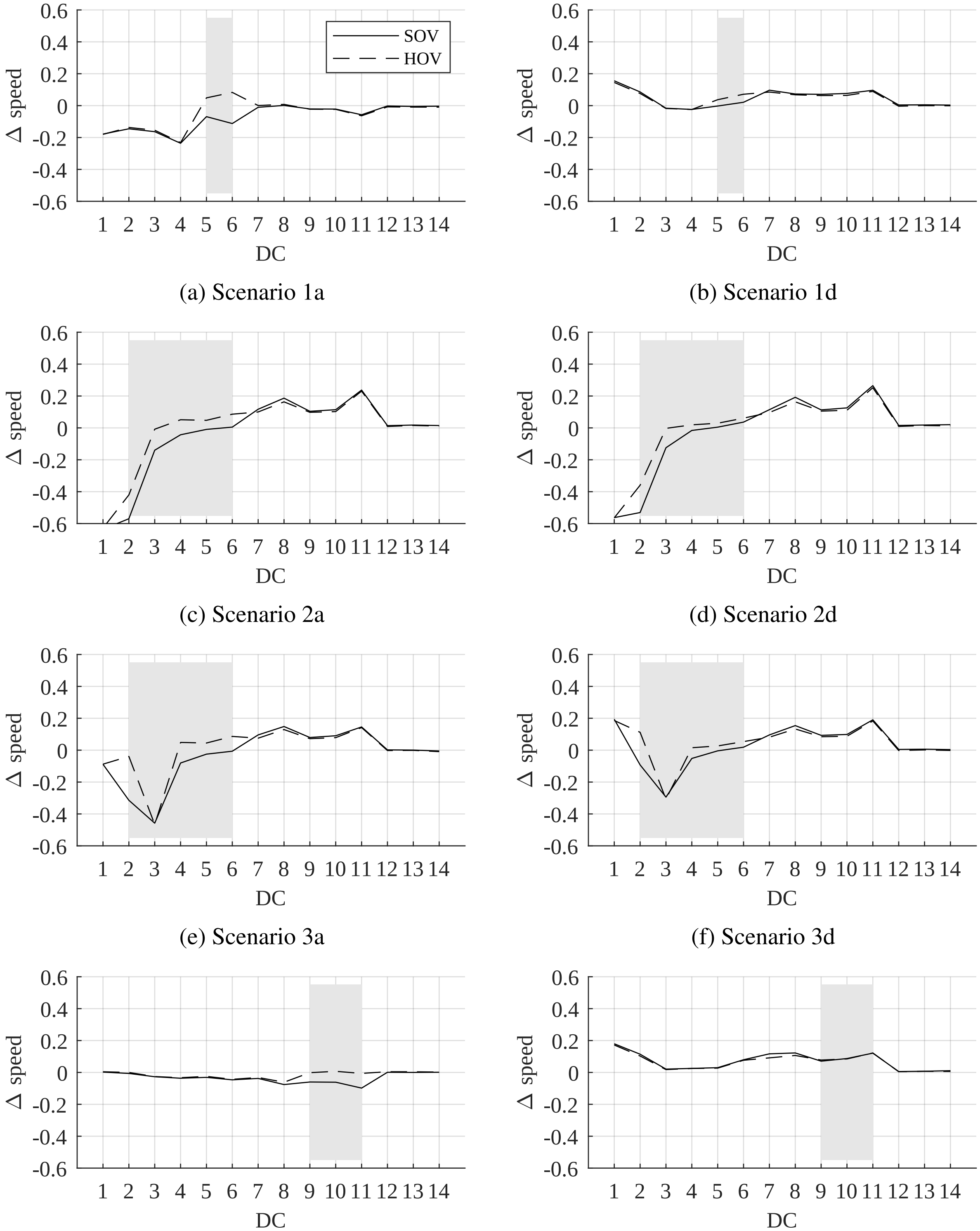
(e) Scenario 3a

(f) Scenario 3d

(g) Scenario 4a

(h) Scenario 4d

FIGURE 5 : Travel Times from DC01 to DC14 (19.5 km) in the Scenarios



(a) Scenario 1a
(b) Scenario 1d
(c) Scenario 2a
(d) Scenario 2d
(e) Scenario 3a
(f) Scenario 3d
(g) Scenario 4a
(h) Scenario 4d

FIGURE 6 : Mean Relative Speed Difference between Baseline and Scenarios at 14 Data Collection Points (DC on HOV Lane Highlighted in Gray)

which could lead to the problems described. Further research on these effects of lane changing would be useful.

The simulation indicates that HOV lane design 1 offers no incentives for carpooling as HOVs do not have lower travel times than SOVs. An increase in vehicle occupancy and thus an improved situation for all road users is not to be expected under these circumstances.

With HOV lane design 2 we evaluated whether a spatial shift of additional lane changes into the area upstream from the intersection area leads to less congestion. Scenarios 2a to 2d show increased travel times for all the road users compared to the baseline scenario. In the four scenarios, HOVs are about 2 minutes faster than SOVs. An increase in vehicle occupancy does not improve the overall situation. However, the advantage of HOVs over SOVs remains. The mean speed differences show a significant speed drop in the intersection area (DC01 - DC04). In the two-lane intersection area, 50% of the capacity is restricted to HOVs. The remaining lane cannot cope with the number of SOVs and congestion occurs. Both HOVs and SOVs are affected, even though HOVs need less time to pass the congestion because of the HOV lane. HOV lane design 2 offers small advantages for HOVs over SOVs. However, the overall situation of all road gets worse for all scenarios 2a to 2d so that design 2 is no advisable solution.

With HOV lane design 3 we analyzed whether the release of the hard shoulder in the intersection area can prevent the capacity problem from design 2. The capacity of the general purpose lanes remains the same, and additional capacity is provided for HOVs. With the current vehicle occupancy of 1.20 passengers per vehicle (scenario 3a), travel times increase slightly for SOVs compared to the baseline scenario. HOVs have travel time savings of about 4 minutes compared to SOVs. An increase in vehicle occupancy improves the situation for all road users. The advantage of HOVs over SOVs remains but diminishes to about 3 minutes. The mean speed differences show a significant speed drop at DC03. As illustrated in figure 4, there is a lane drop downstream from the intersection for design 3. This decrease from five to four lanes involves merging traffic, which causes congestion measured by data collection point DC03. HOV lane design 3 offers advantages for HOVs over SOVs. However, it is questionable whether travel time savings of about 4 minutes are enough to promote carpooling.

With HOV lane design 4 we analyzed the effects of a dynamic link between an HOV lane and the existing temporary hard shoulder running. In scenario 4a, travel times increase slightly compared to the baseline scenario, both for HOVs and SOVs. The mean speed differences show slightly lower speeds than in the baseline scenario. On the HOV lane, HOVs are faster than SOVs. An increase in vehicle occupancies (scenarios 4b - 4d) leads to lower travel times for all road users, but there are no advantages for HOVs over SOVs. HOV lane design 4 offers no incentives for the formation of carpools and an increase in vehicle occupancy is not to be expected under these circumstances.

One reason for the limited success of an HOV lane on a German freeway is the total number of lanes. In contrast to US freeways with six or more lanes in one direction, Germany's busiest freeways have usually three, in rare cases four lanes per direction. The conversion of a general purpose lane into an HOV lane therefore means a reduction of general purpose lane capacity of 25% to 33%.

CONCLUSIONS

We developed a microscopic traffic flow model of a section of a German federal freeway in Vissim. The driving behavior was calibrated with measured traffic data. We used this model to simulate 16 scenarios of an HOV lane (four HOV lane designs combined with four vehicle occupancies). Travel times and speeds in the scenarios with HOV lane were analyzed and compared to the baseline scenario without HOV lane.

The survey showed that the desired effects of an HOV lane can only be achieved to a small extent. By restricting a general purpose lane to an HOV lane, traffic congestion on the remaining general purpose lanes should initially become worse, while traffic flows on the HOV lane. This leads to travel time savings as well as higher driven speeds for HOVs. These benefits for HOVs over SOVs should motivate the formation of additional carpools so that the overall traffic volume decreases, and the situation of all road users improves.

For all four HOV lane designs, HOVs are able to drive faster on the HOV lane than SOVs on the general purpose lanes. With increasing vehicle occupancy, the speeds of HOVs and SOVs converge since the number of vehicle increases on the HOV lane. For two HOV lane designs, the achievable travel time savings for HOVs are negligible. An increase in vehicle occupancy is therefore not to be expected. For the other two designs, HOVs can save up to 4 minutes travel time compared to SOVs. But for both designs there is a significant speed drop upstream from the HOV lane in the simulation. For one design, this results in much higher travel times for all the road users compared to the baseline scenario, regardless of vehicle occupancy.

We conclude that the reduction of general purpose lane capacity is too high when introducing an HOV lane. Furthermore, in the simulation an HOV lane results in additional lane changes in the upstream area from the HOV lane. The reduced capacity in combination with increased lane changes leads to congestion, both for HOVs and SOVs. Only on the section of the HOV lane itself, HOVs are faster than SOVs. Downstream the traffic situation remains the same as in the baseline scenario. Therefore, the potential for travel time savings for HOVs compared to SOVs is low.

With the current vehicle occupancy, only one HOV lane design leads to travel time savings for HOVs compared to the baseline scenario, while the travel times for SOV increases. If the benefit of the HOV lane changes people's mobility behavior towards carpooling, we showed that travel time reductions are possible for all road users, while the advantage for HOVs over SOVs remains. However, it is questionable whether a minor time gain is enough to change people's mobility behavior towards carpooling.

In the context of further investigations, an extension of this scenario should be examined to determine whether long-term advantages for HOVs are achievable. It is also recommended to investigate the people's behavioral change with regard to carpooling. Based on the findings on additional lane changings, the differences between European and American transport infrastructures should be examined more closely. The question arises as to what influence speed differences between different lanes have on the capacity of a section equipped with an HOV lane. Furthermore, the potential for travel time savings due to an HOV lane should be extended from the morning peak period to an entire day.

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AUTHOR CONTRIBUTION

The authors confirm contribution to the paper as follows (in alphabetical order): study conception and design: H.S. Buck, P. Vortisch, C.M. Weyland; modeling and simulation: C.M. Weyland; analysis and interpretation of results: H.S. Buck, C.M. Weyland, V. Zeidler; draft manuscript preparation: H.S. Buck, P. Vortisch, C.M. Weyland, V. Zeidler. All authors reviewed the results and approved the final version of the manuscript.

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