Paper ID 891

Investigation of the system-wide effects of intelligent infrastructure concepts with microscopic and mesoscopic traffic simulation

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Abstract

In this paper we present a case-study for the greater area of Düsseldorf and investigate the effect of intelligent infrastructure on modal share, travel times and travel distances. Our approach combines the microscopic simulation SUMO to obtain traffic-flow capacities for signalized intersections, with the mesoscopic simulation MATSim to investigate system-wide and long-term effects. We investigate multiple scenarios with decreased, as well as increased flow capacities as consequence of innovative infrastructure and vehicle technologies. This study highlights the importance to account for both short-term and long-term effects. An increase in flow capacities at intersections yield a short-term effect of reduced travel times. However, in the long run, the more attractive car mode leads to an increase in car trips and total vehicle-kilometers (rebound effect) which may yield negative side effects such as increased air pollution and noise.

Keywords:

Simulation & Modelling; Intelligent infrastructure

Introduction

Autonomous vehicles (AVs) will undoubtedly have a large impact on future traffic systems and mobility across all sectors. Equipped with intelligent sensing devices and communication capabilities, it is projected that AVs will be able to drive safer and more efficiently than human drivers in the future. An additional push may come with the integration of intelligent infrastructure that allows to exchange information for more efficient route planning and intersection control.

Apparently, this transition to autonomous driving will not be instantaneous but requires years of development and testing in order to gain significant adoption in the general public. Thus, traffic in the near future will be characterized by conventional vehicles mixed with AVs in varying shares. Even today, many OEMs already started testing their AVs and advanced driver assistance systems (ADAS), partly on publicly accessible roads. Test fields with intelligent infrastructures are currently built and evaluated in many cities or regions[1].

While there is a lot of ongoing research to solve conceptual, technical and ethical challenges associated with autonomous driving, it is also worth to investigate the system-wide effects that these technologies have on our traffic systems.

In this paper, we conduct a study on the German city *Düsseldorf*, which is part of a national test field for automated and connected driving[2]. First, we describe our simulation approach that combines microscopic with mesoscopic simulation. Afterwards, we describe the scenario and characteristics in detail and subsequently present the simulation result. The presented transport model is also available as an open-source application with publicly available data[3].

[1]see e.g. https://www.bmvi.de/DE/Themen/Digitales/AVF-Forschungsprogramm/Projekte/avf-projekte
[2]`https://komodnext.org/`
[3]`https://github.com/matsim-scenarios/matsim-duesseldorf`

The ability of AVs to communicate with traffic infrastructure allows for faster, better informed and more "intelligent" decision-making. Several algorithms for optimized intersection control have been proposed in the literature [1–3]. In the case of fully autonomous traffic, these control mechanisms may work without any traffic signals, only by communication between the participants. On such intersections the flow capacity would be massively higher and delay time greatly reduced [2, 4]. The same applies to road sections where multiple vehicles merge into one lane [5, 6].

However, especially during the transition phase with mixed traffic, the flow capacity of roads does not necessarily increase. For instance, if AVs drive defensively with a lot of headroom to other vehicles, the flow capacity can decrease substantially on motorways [7], as well as on intersections [8].

Gucwa also studied the system-wide impact of automated cars [9], for which he used a synthetic population with an activity-based model in the San Francisco Bay Area. Their results suggested a 4-8 % increase in daily vehicle miles. They do assume increased road capacities of 10 % and 100 % in their scenarios.

Maciejewski & Bischoff use an agent-based transport model to investigate the impact of autonomous taxi fleets on the congestion level in Berlin, Germany [10]. They simulate different estimates for the increase in flow capacity and find that even a moderate increase in flow capacity by 1.5 yields a reduction in traffic congestion despite higher traffic volumes due to empty pick-up trips.

Given multiple plausible scenarios, there is no clear picture yet how the traffic capacities are going to develop in the near future. For this reason, we will perform our analysis on multiple scenarios with decreased or increased flow capacities.

Methodology

Our approach is to combine the microscopic simulation *SUMO* [11] with the mesoscopic agent-based simulation *MATSim* [12] in order to evaluate system-wide effects. Figure 1 shows our general simulation approach, which can be summarized as follows:

1. Extracting road network information from OSM data.
2. Simulating intersections in *SUMO* microscopically in order to obtain maximum vehicle flows for each lane at all signalized intersections.
3. Transferring the network structure and flow capacities to *MATSim*.
4. Calibrating the model with demand data and survey results.
5. Sensitivity analysis with adjusted flow capacities.

SUMO

Microscopic traffic simulation is an essential tool for various applications in the areas of traffic planning, operation and academical research. The overall aim of a microscopic traffic simulation is to capture the behaviour of individual vehicles respectively drivers and especially the interactions between them in a detailed manner. This includes a representation of the road network with its infrastructure elements (e. g. traffic lights) as well as travel demands (i. e. route choice) and the actual driving behaviours (i. e. speed/ acceleration, lane changing, gap acceptance, driver imperfection, etc.).

For this purpose, several software packages with different orientations and application focuses have been developed over the past decades. These include both commercial and academic solutions. One of these solutions is the open source traffic simulator "SUMO" (Simulation of Urban MObility, see: https://www.eclipse.org/sumo) [11]. The tool SUMO is freely available and published under the Eclipse Public License V2. Although it started as a purely academic playground, SUMO has evolved very rapidly since its beginnings in 2001. Several model extensions, simulation enhancements and improvements have been implemented by employees of the Institute of Transportation Systems at the German Aerospace Center (DLR) together with an international community.

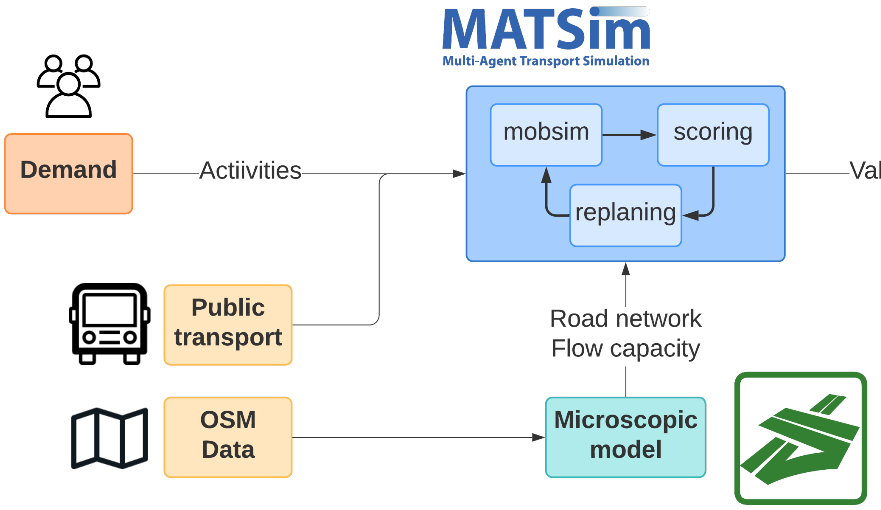

Figure 1 – Overview of the simulation approach combining microscopic with mesoscopic simulation

SUMO is a highly portable, microscopic and continuous traffic simulation package designed to handle large traffic networks. It allows for an inter-modal simulation including pedestrians, bicycles and several means of public transport. The – often time-consuming and difficult – process of preparing and running a traffic simulation is supported by a large set of tools for generating, converting and editing traffic networks as well as travel demands and additional data. The SUMO package provides command line versions of these programs for rapid use and the integration/ interaction within scripts. However, GUI applications are also available of the actual simulation program (SUMO GUI) and the editor for working with road networks, traffic demands and auxiliary data (NETEDIT). These GUI applications support a simpler workflow on the one hand and enable a qualitative validation on the other hand. Moreover, SUMO provides a programmable interface called "TraCI" (Traffic Control Interface) for exchanging information and manipulating various parameters even during the run-time of simulations. In addition, easy coupling to other simulators (e. g. simulation of message networks, emission models, etc.) is supported.

MATSim

In the agent-based and dynamic transport simulation framework MATSim (Multi-Agent Transport Simulation, see https://www.matsim.org) [13], each transport user is modeled as an individual agent. Each agent's behavior is described by a daily travel plan which contains the activity-trip-chain and related information (activity end times, transport modes, network routes). The agents are enabled to adjust their travel behavior in an iterated manner which may be akin to a learning process. For the adaptation of transport demand to transport supply an evolutionary iterative approach is applied which involves the following three steps:

1. The traffic flows are simulated. Transport users interact on the same network applying a queue model which accounts for dynamic congestion and spill-back effects. Each road segment (link) consists of several network lanes which are modeled as a *First In First Out queue* [14] with the attributes length, free speed and flow capacity and information about turn restrictions. Every second, the state of each queue is updated. A vehicle is only moved to the next road segment if (i) the free speed travel time has passed, (ii) the inverse of the flow capacity has passed since the last vehicle left (available flow capacity), and (iii) there is space on the next road segment (available storage capacity).

2. The agents evaluate their daily (travel) behavior based on the travel-related costs, e.g. mode-specific fixed cost and travel time costs, tolls, fares, and the time spent performing activities, such

as *home*, *work*, or *shopping*. For the latter, a logarithmic utility is applied, where the marginal gain is positive but decreases with time [15].

3. The agents are enabled to adjust their travel behavior. During choice set generation, every iteration a predefined share of agents clones an existing travel plan and applies some mutations, e.g. switch to another mode of transportation, generate a new network route, adjust the departure time. In this study, activity locations are fixed and not changed by the agents. During choice set selection, agents choose among their existing choice sets based on a multinomial logit model.

Repeating these steps over several hundreds of iteration enables the outcome to stabilize and the agents to improve and obtain plausible daily travel plans. Assuming each agent's set of daily travel plans to represent a valid choice set, the outcome approximates the stochastic user equilibrium [16, 17].

Simulation setup

In this study, simulation experiments are carried out for Greater Düsseldorf area, Germany. The synthetic population is provided as an excerpt from the nation-wide MATSim model of Germany by Senozon Deutschland GmbH[4]. For population generation a data fusion approach is applied which takes into consideration survey data as well as anonymized mobile phone data. For an in-depth information of the applied demand generation methodology, in particular the Mobility Pattern Recognition, see [18]. The population includes all persons traveling from, to or through the city of Düsseldorf. Thus, resulting travel patterns cover the entire area of Germany. To improve the computational performance and reduce the network size, the least relevant agents (most time spent outside the Düsseldorf area) are removed. The initial mobility demand represents a typical work day in the year 2019. The model also includes transit schedules for public transport, which have been imported as GTFS data from local transportation services. Key characteristics of the scenario are summarized in Table 1.

Table 1 – Simulation scenario key characteristics

Open MATSim Düsseldorf model	
Number of agents	213,425
Agents living in Düsseldorf	131,589
Trips of residents per day	304,428
Number of links	739,098
Signalized junctions	7,333

Obtaining maximum vehicle flows

Based on this OSM raw data, all traffic signal-controlled intersections were analysed to determine the maximum traffic flow possible for each individual lane. For this purpose, the SUMO interface TraCI was used, which allows the interaction with a running traffic simulation and the modification of objects or their behaviour. Using TraCI, vehicle flows of up to 2,000 veh/h were applied to probe the capacity of each individual lane of each intersection controlled by traffic lights. The traffic signals were modelled as traffic-adaptive systems that react to the magnitude of the respective traffic flows. In this way, the theoretical maximum possible traffic flow per lane could be determined for all the 7,333 traffic signal-controlled intersections in the study area. The following Figure 2 shows a histogram of the determined maximum flows in vehicles per hour. In general, the distribution obtained corresponds to the expected assumptions The median value equals 1,164 veh/h, the maximum value is 1,667 veh/h.

There are a total of four different intersections in the data set that have individual lanes with a maximum flow of 0 veh/h, i. e. no traffic flow at all. However, this only relates to transitions from roads to bus or cycle lanes, where private vehicles are not allowed to drive.

[4] www.senozon.com

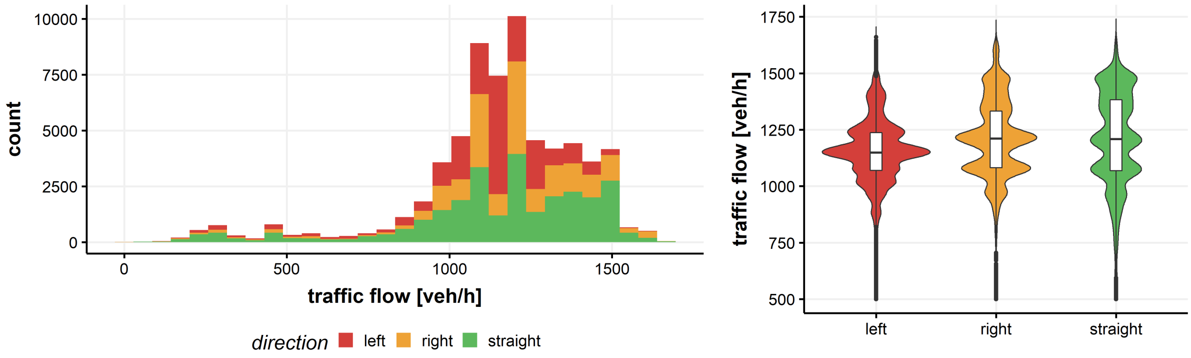

Figure 2 – Histogram of the theoretical maximum traffic flows for all lanes in front of all 7,333 traffic signal-controlled intersections in the study area.

In addition, there are a total of nine junctions which have lanes with a flow greater than 0 and less than 100 vehicles per hour. This very low traffic flow (in some cases only 11 veh/h) is always due to network errors in the unprocessed OSM network. Figure 3 shows an example of such network defects. In order to correct them, a costly and labour-intensive network correction and post-processing would be necessary in these cases. However, the method proposed here makes it somewhat easier to find those faulty intersections. The high values for the maximum possible flow greater than 1,600 veh/h that can be observed in Figure 2 generally represent traffic signals at junctions of smaller roads and not at intersections of roads with the same or similar priority, as shown in the following Figure 3. Since vehicles simply continue straight ahead here without having to reduce speed, e. g. when turning, higher values for traffic flow are possible in these cases.

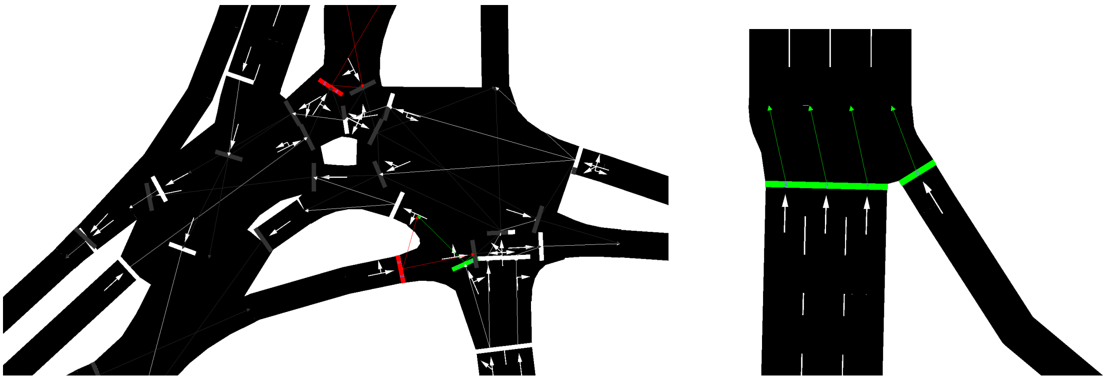

Figure 3 – Example of an intersection with network defects and thus significantly reduced traffic flows (left); Example of traffic lights at junctions of roads with different priorities. Link indices 1 to 3 with higher priority have very high potential traffic flows (right).

The queue model in MATSim was configured, according to the obtained flow capacities and such that vehicles consume capacity depending on their turn direction, e.g. the flow capacity is lower on left turns with oncoming traffic. All intersections with implausible traffic flows are not considered in this study. Other roads and remaining intersections have traffic flow values according to their road type and default values in MATSim.

Model calibration

To calibrate the mesoscopic model we run MATSim for 350 iterations to reach a traffic equilibrium. The number of iterations was chosen such that the modal split was able to converge and not change anymore with further iterations.

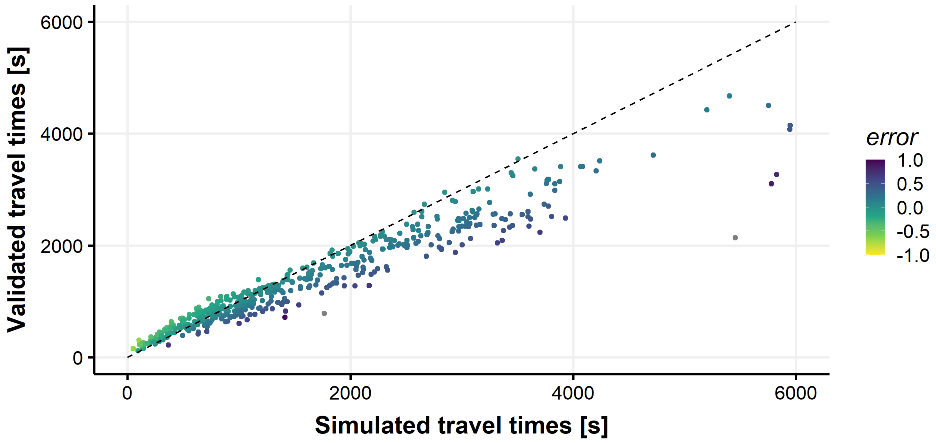

Figure 4 – Simulated travel times vs. travel times obtained from routing API using shortest-route; The color indicates the relative error.

Until iteration 250, agents are allowed to explore all possible modes and store the gained experience in form of the obtained utility of the executed plan. After iteration 250, agents only select plans from their experience with a multinomial logit model on the expected utilities and perform rerouting to account for current traffic situation. Survey data from "System repräsentativer Verkehrsbefragungen" (SrV) 2018 [19] is then used to calibrate the utility model. Marginal utilities of all traffic modes have been adjusted, such that the modal split from the simulation matches the SrV survey data as closely as possible. The overall car share in the calibrated scenario (27.9%) is very close to the survey data. Small differences in the other modes are not as significant, as this is mostly a car focused study.

Not only the modal split is important, but also the absolute number of trips. Since simulated travel demand is only a sample of the real-world population in the Greater Düsseldorf area, flow and storage capacities are accordingly reduced in order to reproduce realistic traffic congestion effects. The 612.178 inhabitants of Düsseldorf perform on average 3.5 trips resulting in a total of 2.1 mio trips on a weekday[5]. Given 304.428 trips from our demand sample, network capacities have been down-scaled by a factor of 0.14. Down-sampling factors between 0.1 and 0.25 or even below 0.1 have been used in various MATSim applications [13].

We also validated our road network and compared observed travel times in the simulation with expected travel times provided by *HERE* API. Figure 4 shows that the travel times are slightly higher in the simulation for long trips (10% higher travel time on average) which might be due to changed mobility behavior during the pandemic.

Simulation experiments

The calibrated scenario serves as baseline for further comparisons. To model the effects of intelligent infrastructure, the flow capacity at all traffic light controlled intersections is modified. The variations are 60%, 80%, 120% and 140% of the original capacity. These values reflect the approximate effect as taken from the literature. Values below 100% corresponds to scenarios, in which AVs drive defensively and the overall flow capacity is reduced. However, in the long run with more mature technology we expect that overall flow capacity is increased, which is represented by the scenarios 120% and 140%.

Using this as base setup, we are interested in two types of effects:

Short-term (ST) Agents' initial choice sets are taken from the base case, including already experienced travel alternatives. Plans are only adapted by rerouting and departure time mutation to account for

[5]Data can be accessed at `https://tu-dresden.de/bu/verkehr/ivs/srv/ressourcen/dateien/SrV2018_Staedtevergleich.pdf`

the current traffic situation. This allows to observe changes in travel times or congestion patterns, without any long-term adaption.

Long-term (LT) Choice dimensions of agents are the same as in the base scenario. This allows to observe potential rebound effects, e.g agents switching to car because of reduced road capacities.

The modified traffic flow is applied uniformly across all traffic light controlled intersections. We do not consider increased free-flow speeds, i.e. maximum allowed speeds are unchanged in all scenarios.

Results

Table 2 summarises the car share, traveled person kilometers and traveled person hours for the car mode across all scenario variations. The evaluation only includes trips with origin and destination within the city boundaries of Düsseldorf.

Table 2 – Comparison of base scenario with short- (ST) and long-term (LT) effects of different variations of flow capacity at signalized intersections; all numbers refer to trips with origin and destination in the Düsseldorf city area

Flow capacity	100%	60%		80%		120%		140%	
	Base	ST	LT	ST	LT	ST	LT	ST	LT
Car trips	350.6k		−12.3%		−4.2%		+2.3%		+4.6%
Vehicle-km	1.97m		−10.5%		−3.3%		+2.2%		+4.1%
Vehicle-hours	74.4k	+8.0%	−3.7%	+1.0%	−0.1%	−2.7%	+1.3%	−3.2%	+0.7%

* values with no significant change have been omitted

The short-term scenarios show a rather intuitive pattern. Reduced road capacities (60%, 80%) yield an increase in vehicle-hours and increased road capacities (120%, 140%) yield a decrease in vehicle-hours. In the most pessimistic scenario for example, travel times increase by 8%. The long-term scenarios show a completely different picture. In the long-term scenario, an opposite effect is observed compared to the short-term scenarios since transport users switch from or to the car mode. In the optimistic scenarios (120% and 140% flow capacity), a rebound effect is observed since in the long run more users switch to the car mode and thus car trips increase by 2.3% and 4.6%, respectively. In the pessimistic scenarios (60% and 80% flow capacity), users switch from car to other modes of transportation and thus vehicle-hours decrease in the long-run (reverse rebound effect).

Congestion at peak hours

Figure 5 shows congestion patterns during the afternoon peak for the inner city area of Düsseldorf.

This figure clearly shows the overall higher travel speed and less congested links as the short-term effect of having an increase in flow capacity of 140%. Especially the *Fleher* bridge and *Josef-Kardinal-Frings* bridge crossing the *Rhine* river are significantly less congested. However, the long-term effect will be different due to the rebound effect and the overall increase in traffic volume.

Conclusion

This study investigates the impact of future infrastructure and vehicle technologies on the overall transport system. The microscopic transport simulation SUMO is used to derive realistic flow capacities for traffic light controlled intersections in the base case. These capacities are transferred to the mesoscopic transport simulation MATSim and systematically adjusted to parameterize the effect of future infrastructure and vehicle technologies.

Figure 5 – Relative travel speeds at 17:00-18:00 in the base scenario (left) and in the short-term scenario with 140% capacity (right). Yellow links indicate a relative speed below 50% compared to freeflow speed; Red links indicate a relative speed below 10% compared to freeflow speed.

Our study shows that AVs driving very defensively at intersections may on the one hand increase road users' travel times. On the other hand, road users may avoid the increase in travel times by switching to alternative modes of transportation.

Intelligent infrastructure and control systems for AVs have the potential to increase the efficiency of the transport system. This study highlights the importance to account for both short-term and long-term effects. As shown in our results, an increase in flow capacities at intersections yields faster traveling in the short-term but also makes the car mode more attractive. In the long-term, a more attractive car mode leads to an increase in car trips and total mileage which may even fill up the additional road capacities (rebound effect). The increase in road traffic volume may then lead to an increase in noise exposures and air pollution. Additionally, advantages of AVs, such as improved safety or a higher level of travel comfort could also induce even more people to use the car mode instead of more environmentally friendly alternatives. Therefore, we think it is of utmost importance to invest in renewable energies and sustainable drive technologies. Otherwise, the use of combustion engines will cause considerable environmental damage, even more than today. Furthermore, to make full usage of intelligent infrastructure and vehicle technologies, additional regulatory policies are required to avoid the rebound effect and to discourage users from switching to private motorized transport.

As next step, intelligent infrastructure concepts will directly be modeled in SUMO and resulting capacities will be transferred to the mesoscopic simulation MATSim. This allows for an improved investigation of such technologies and provides the basis for an economic evaluation of an infrastructure roll-out. With access to the national test-field in Düsseldorf, we also plan to test some of these intelligent infrastructure concepts in practice and validate the obtained simulation results.

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