Impacts of Automated Vehicles on Traditional Road Traffic

Thesis by:
Qiong Lu

MŰEGYETEM 1782

Department of Control for Transportation and Vehicle Systems
Budapest University of Technology and Economics

Supervisor:
Dr. Tamás Tettamanti

Submitted in Partial Fulfillment of the Requirements for the Degree of
Doctor of Philosophy

October 29, 2021

1 Introduction

The emergence and increasing applications of AVs challenge the existing traditional transportation system. At present, all static and dynamic traffic management techniques are prepared for the human driver generated traffic flow. However, the traffic composition of AVs dictates more complex requirements and control tasks to be met because AVs driving behaviors might significantly differ from traditional human driven cars. For example, the time headway may vary along with the penetration of AVs [TVS16]. In the macroscopic traffic modeling, one of the most exciting changes is presented by the effect that driverless cars bring to the well-known traditional traffic model, the Macroscopic Fundamental Diagram (MFD). MFD is a basic model for strategic traffic planning and also for real-time traffic control. MFD can be utilized to describe the service level as well as the throughput of a traffic system. When applying inflow regulation or speed limits to the road, the MFD is also valid to define the traffic dynamics. The MFD is functional for both freeway and metropolitan areas traffic as proposed by [God69]. The idea of urban MFD has been generally researched amid the previous decades [MWH87, Dag07, KEPP14, CTV15]. Introducing AVs to the road network can change MFD because it can improve capacity by i) keeping traffic flow parameters steady, and ii) taking into account faster responded, more tightly spaced vehicles [KTSH08, TM16, TME17, VAVDV06].

The cooperative intelligent transport system (C-ITS) is a technology applying vehicle-to-everything (V2X) communications to improve road safety and traffic efficiency [SABB17]. This technology can work as a central controller providing a probability to control the vehicle's route choice in the routing phase. In addition, the emergence of robo-taxi and the spreading of Mobility-as-a-Service may bring the direct central control into reality, i.e. the system-optimal flows can be obtained. Accordingly, [PT19] defined a linear programming method utilized to realize the system optimum (SO) traffic assignment in an intelligent and autonomous transportation system. Another way to realize the system optimum is to apply a congestion pricing strategy. It is the passenger's failure to notice the total cost they add that causes the difference between user optimum and system optimum. Any additional passenger of a network is a marginal user. He/she can only perceive the private cost rather than the social one. In order to achieve system optimum, passengers must be made aware of the total cost they put on others. By applying a congestion pricing strategy, every trip-maker can be made realize the marginal cost caused by he/she [BMW56, D^+79].

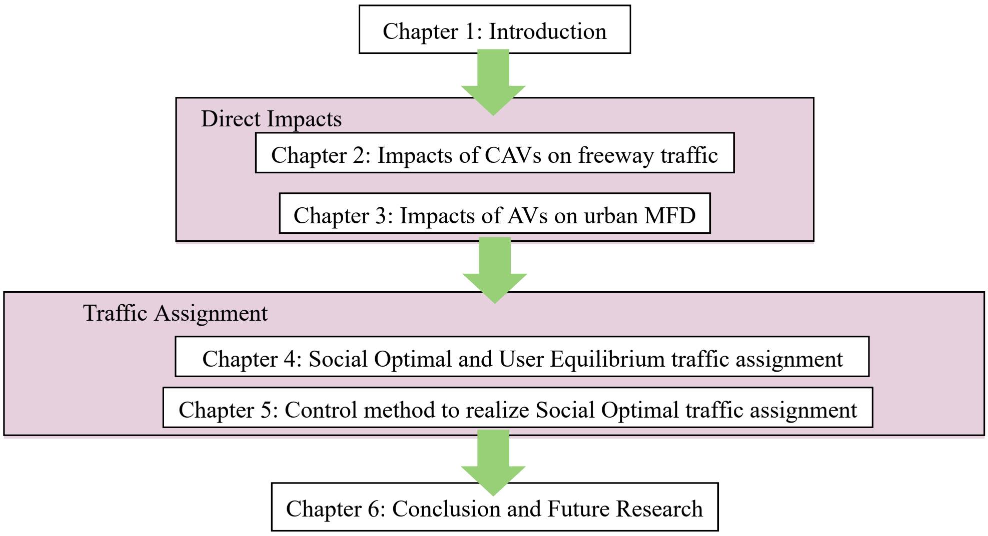

Figure 1: Structure overview of the dissertation

The purpose of this dissertation is to find out the impacts of AV/CAV on the conventional traffic system of freeway and urban transportation systems. Besides the direct changes, the dissertation also talks about SO traffic assignment, which is possible to come to reality along with CAV. A control method to realize the SO traffic assignment is proposed and verified with a simulation. The structure overview of the dissertation is illustrated by Fig. 1

2 Research goals and methods

3 Contributions of the Thesis

Thesis 1

The impacts of Connected Automated Vehicles (CAVs) on the freeway have been investigated. A thorough sensitivity analysis was carried out on time headway, CAV penetration, as well as the speed limit concerning the impacts of traffic flow, fuel consumption, and emission. The analysis justifies that a higher speed limit contributes to a faster free-flow speed and a more substantial road capacity. At the same time, it weakens the stability of the flow. Reducing time headway in a certain range (depending on the given freeway link's feature) results in lower fuel consumption and emission. When the time headway is lower than this defined range, the energy consumption

and emission increase sharply. Consequently, a recommended optimal time headway must be found to balance the CAVs' impacts on the road capacity and fuel consumption.
[MLT19, LT21a]

The contribution of this thesis is twofold. First, the shorter the time headway is, the higher the maximum flow becomes. Reducing time headway in a certain range may result in lower fuel consumption and emission. When the time headway is lower than this range, the energy consumption and emission increase sharply. From the perspective of fuel economy and environment, a recommended optimal time headway must be found. Second, a higher speed limit contributes to a faster free-flow speed and a more substantial road capacity. At the same time, it weakens the stability of the flow. The speed limit differs from country to country. Few papers investigate the CAV under different speed limit scenarios. This thesis provides an insight into the impacts of varying speed limits when it comes to CAVs.

The fundamental diagram is a well-acknowledged theory to characterize freeway traffic dynamics in a macroscopic way. In this approach averaged traffic flow variables are considered on a given road stretch, i.e. traffic density k (vehicles/km), space mean speed $V(k)$ (km/h) depending on k, as well as traffic flow $Q(V(k))$ (vehicles/h). These three parameters are related via the following equation adopted from fluid dynamics.

$$Q(V(k)) = V(k) \cdot k \tag{1}$$

A wide range of diverse forms of fundamental diagrams is available in the literature [CB12]. One practical form of the fundamental diagrams (which well reflects the real-world observations on freeways) is proposed by [New93], i.e. the triangular flow-density relationship.

$$Q = \min \{v \cdot k;\ w \cdot (k_j - k)\},\ for\ 0 \le k \le k_j \tag{2}$$

Where v is free-flow speed, k is vehicle density, w means the backward wave speed, as well as k_j stands for the jam density. The freeway link, in this work, is assumed to follow the kinematic wave theory with all lanes having the same free-flow speed v and the same backward wave speed w, see Fig. 2.The maximum flow Q_m is derived as follows.

$$Q_m = \frac{k_j w v}{w + v}. \tag{3}$$

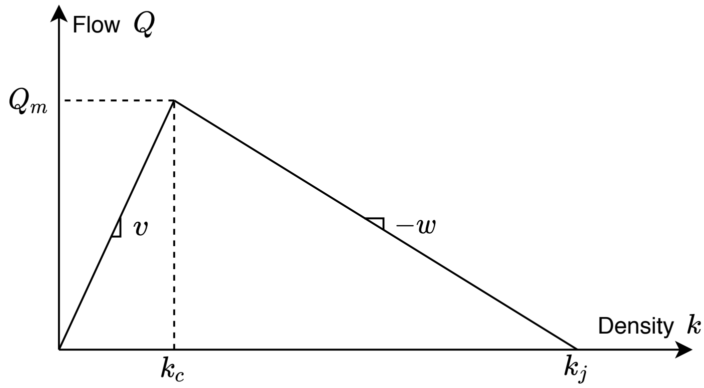

Figure 2: Triangular Fundamental Diagram

As shown in Fig. 3, a real-world network was selected for simulation based analysis. The test network is a 10 km section of the European designation E60 (Hungarian highway M1) near Herceghalom city. The base data for geometry, traffic flow, as well as other road features were gathered directly from the open database of Hungarian Public Roads.

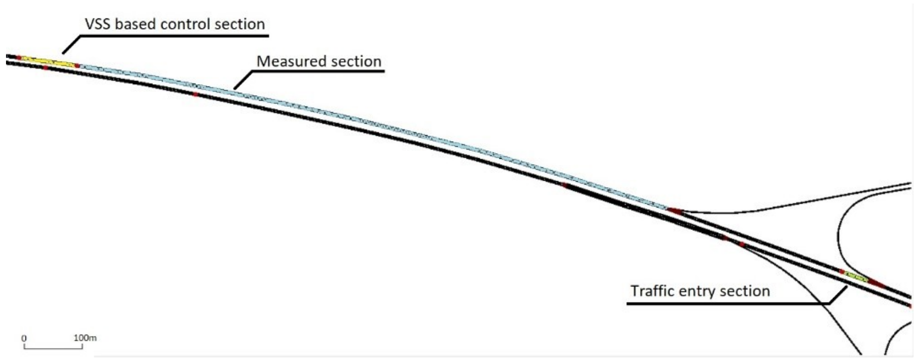

Figure 3: The network used in the simulations

In this research, a sensitivity analysis was carried out investigating three parameters: reaction time, CAV penetration, and the speed limits to find their impacts on the MFD, the throughput of the highway, and the energy consumption and air pollution of vehicles.

A detailed sensitivity analysis has been carried out on time headway, CAV penetration, as well as the speed limit. The impacts on freeway traffic flow, fuel consumption, and emission have been investigated. As shown in the result section, the free flow speed v is relatively stable when CAVs penetration and time headway changes. The wave speed w increases substantially when the time headway becomes shorter. Furthermore, it can be concluded that the shorter the time headway is, the higher the maximum flow becomes. At the same time, fuel consumption drops with the increase of CAV penetration when the CAV time headway is longer than 0.5 seconds and the speed limit is 80 km/h. On the contrary, when time headway is shorter than 0.5 s, fuel consumption and CO_2 emission increase sharply while CAV penetration increases. Therefore, reducing time headway in a certain range may result in lower fuel consumption and emission. When the time headway is lower than this range, the energy consumption and emission increase sharply. Consequently, a recommended optimal time headway should be found to balance the CAVs' impacts on the road capacity and fuel consumption. The speed limit directly influences the free-flow speed. As the speed limit rises, free-flow speed and road capacity do the same as well. As shown in the result section, the maximum flow increases with the enlarged speed limit in the analyzed scenario. However, when the speed limit is higher than 160 km/h, the measured points around the critical density are more scattered around with the speed limit's rise. A higher speed limit contributes to a faster free-flow speed and a more substantial road capacity. At the same time, it weakens the stability of the flow. In the future, with the optimization of CAV performance, increasing the speed limit might be an effective method to improve the expressway capacity.

Thesis 2

The effects of highly automated as well as autonomous vehicles on the urban Macroscopic Fundamental Diagram (MFD) have been analyzed through microscopic traffic simulation. By using the generalized additive model (GAM), an efficient modeling technique has been developed for urban MFDs with different AV ratios. The results justify clear regularities in the change of the urban MFD (network and link level as well) along with the emergence of autonomous vehicle technology. The capacity is increasing quasi-linearly with higher AV penetration for both grid and real world networks. The critical density and capacity show the same tendency when the level of autonomy and penetration change. Low levels of autonomy and penetration have less impacts on capacity. In contrast, in the high levels of autonomy and penetration scenarios, AVs have great potential to improve road capacity. When self-driving cars start dominating the roads, a plateau occurs around the maximum flow.
[LT18, LTHV20]

This thesis concentrates on the effects of AVs without connected technology by defining the vehicles with different parameters compared to the conventional cars in the SUMO simulator. In addition, the simulation analysis was carried out in two typical urban road networks: a virtual grid network and a real world road system in Budapest. This thesis aims to investigate the possible impacts of AVs on the urban traffic network capacity.

As described in the previous section, the fundamental diagram can be applied at both network-level and link-level. The network-level MFD models the throughput of the traffic network per hour:

$$Q_N(k_a)\,, \tag{4}$$

where Q_N is the number of vehicles that pass through the network. k_a is the average density of the network, and it simply equals the known total number of vehicles in the network divided by the sum of all link lengths of the road network, i.e.

$$k_a = \frac{\sum_{i=1}^{n} k_i l_i}{\sum_{i=1}^{n} l_i}\,, \tag{5}$$

where l_i is the length of link i, n is the number of links [WMIH87, CTV15]. The second approach interprets the MFD of one single road link of the network, i.e.

$$Q_i(k_i) = k_i \cdot V_i(k_i)\,, \tag{6}$$

where Q_i is the flow on the link i, k_i means the density on the link i, $V_i(k_i)$ defines the mean velocity on the link i.

The edge-based measurement of SUMO gave link-level concentration, stop time, overlap travel time, sample second, and average speed.

Concentration k, network average velocity V and flow Q are needed to draw the MFD. The following formulas were used for the calculation of these values.

$$k = \frac{\sum_1^n N_{vi}}{\sum_1^n l_i}\,(veh/km), \tag{7}$$

$$V = \frac{\sum_1^n V_i N_{vi}}{\sum_1^n N_{vi}}\,(km/h), \tag{8}$$

$$Q = \sum_1^n 3.6 \cdot V_i k_i\,(veh/h), \tag{9}$$

where n is the number of the links in the traffic network, V_i and N_{vi} are the average speed and vehicle numbers on the i^{th} link during the measurement interval T.

The average speed is modeled as

$$V(r,k) = \alpha + s(k) + \beta \cdot r + \gamma \cdot r \cdot k\ , \tag{10}$$

where α can be considered as average speed under free-flow conditions, i.e. the intercept of the speed-density function. The $s(k)$ is a non-parametric spline estimated together with the prespecified parameters of the model, α, β and γ. The ratio of AVs among all vehicles (r) enters the regression equation twice.

As illustrated in Fig. 4 and Fig. 5 , a grid road network and realworld urban road networks were created. It was designed to serve as a common situation of the urban road system, especially in the US and Europe, respectively.

This thesis investigated the impact of AVs on urban road network MFDs. This thesis can be divided into two parts: first part investigate the impacts of AV penetration; the following part talks about the impacts of AV ratios and the level of autonomy. Expectedly, AVs have significant potential to improve traffic capacity, efficiency, stability, and safety of existing mobility systems. The scientific literature has already investigated the potential impacts of AVs use on the transportation system, indicating that AVs can

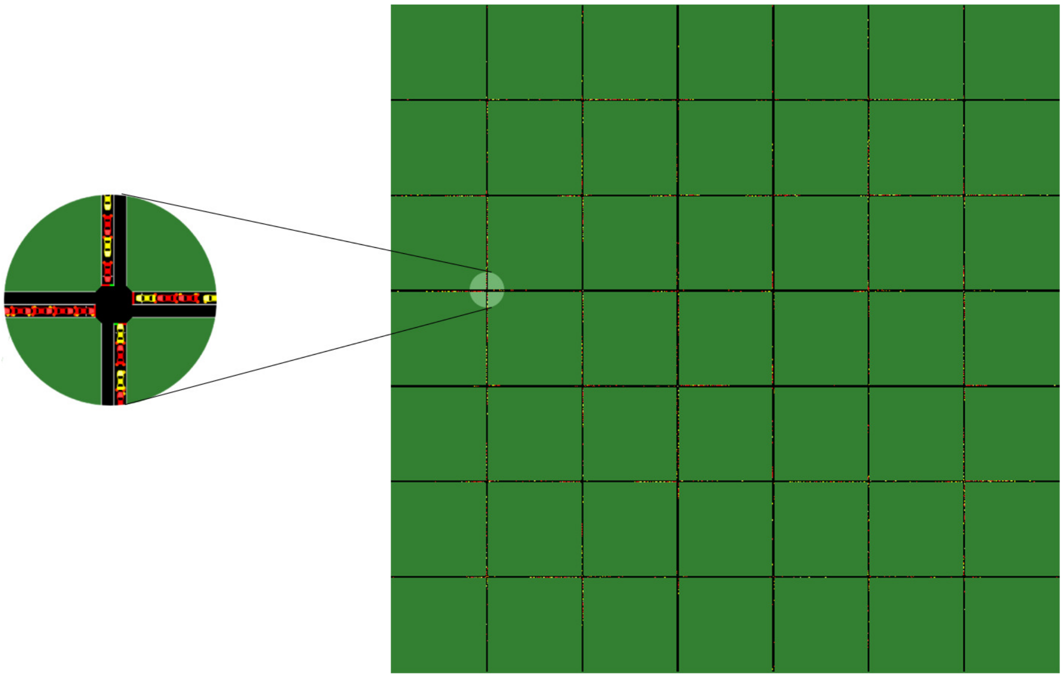

Figure 4: Grid test traffic network

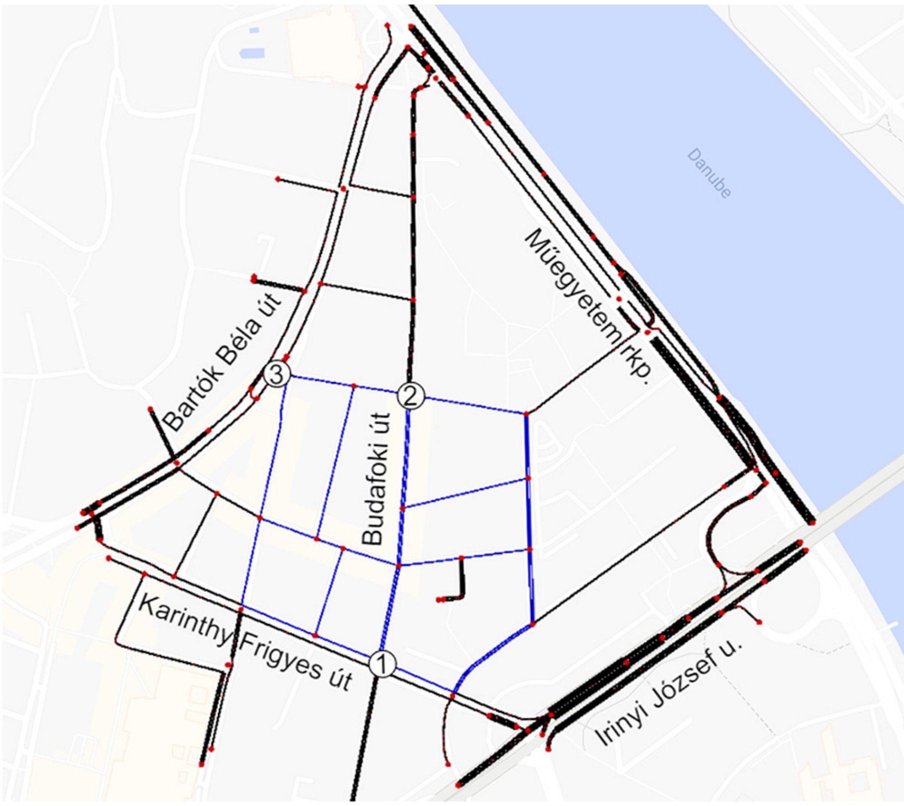

Figure 5: Real world traffic network (GPS coordinates: 47.47733, 19.05358)

improve highway capacity, especially when the penetration is high. However, most of the research works focus on highway capacity improvement, and just a few studies have addressed the impacts on urban transportation with different AVs adoption. To close this gap, three urban road networks were created to represent typical urban environments: two with grid shapes (common in the USA, for instance), and another presenting a typical European network (quite irregular considering the street sizes). The traffic demands increased slowly and smoothly to run the simulation over the entire range of demand conditions. The AVs were simulated in the SUMO traffic simulation suite with different driving parameters compared to the conventional vehicles according to the default car following model (Krauss Model).

In the first part, six scenarios with different AV penetrations (from 0% to 100%) were simulated for both networks. The GAM regression method was applied to fit the speed-AV ratio-density relationship firstly. The R^2 and *p-values* of the estimation show that the GAM is a validated model for estimating the speed-AV ratio-density relationship. This implies that it is a reasonable method to estimate MFD as well. The MFDs were constructed based on the fitted relationship. The maximum flow and critical density for all scenarios could then be determined.

The results show that the capacity is increasing quasi-linearly with higher AV penetration for both grid and real world networks. In the grid network, the maximum flow increases by 16.01% when one compares the 100% AV penetration scenario with only conventional vehicles scenario. This improvement is less than the theoretically calculated result (40%) of [Fri16]. In his work, only a single intersection was taken into consideration which eliminated the accumulation of vehicles on the adjacent roads. That could explain the lower increment of this thesis because the simulations were carried out in road networks. But, [ORAA18] found much fewer benefits (8% improvement) from AVs. His finding could be attributed to the similar headway settings for autonomous vehicles and regular vehicles. The critical density also increases along with higher AV penetration. It increases slowly in the beginning. When AVs adoption arrives at 40%, the critical density increases more intensively.

For the real world network simulation, the total increase of maximum flow is around 25% from the 0% AV penetration to purely AVs scenario. The critical density changes in a similar way to that of the grid network. The critical density increase becomes more intensive around 50% AV penetration. Moreover, there is an obvious plateau around the max flow in the case of 100% AVs on the road.

In the second part, six scenarios with different level of autonomy and penetration were simulated in the grid network through microscopic traffic simulations. The effects of AV on the urban MFD have been analyzed. The results justified some regularity in the change of the urban MFD (network and link level as well) along with the autonomous technology evolution. The critical density and capacity show the same tendency when the level of autonomy and penetration change. Low levels of autonomy and penetration have less impacts on capacity. In contrast, in the high levels of autonomy and penetration scenarios, AVs have great potential to improve road capacity. The results are also important from the point of view of practical traffic engineering as the fundamental diagram is a common modeling approach when planning or analyzing a road network. Therefore, transportation engineers and transportation policy makers should take these changes into consideration in the future.

On the whole, important conclusions can be drawn from the analysis of AV penetration introduced in this thesis. The AV penetration has a positive impact on improving the road network capacity in a quasi-linear way. Maximum traffic flows in the case of 100% AV penetration are 16-23% larger than that of all conventional vehicle scenario. This improvement is due to the shorter headway and less reaction time of AV. Also, the density can augment with higher self-driving vehicle adoption. It increases slowly in the beginning and then intensively around 40% AV penetration. This means the benefit is not obvious when there are not enough driverless cars on the road as the autonomous vehicles must adapt themselves to the conventional vehicles obviously. When self-driving cars start dominating the roads, a plateau occurs around the maximum flow. This phenomenon means that no significant maximum is obtained, i.e. maximum throughput is available on a longer area and not at a dedicated point (critical density of conventional MFDs). With the adoption of 100% AV, the road network becomes more stable and can avoid getting congested easily to some extent.

Thesis 3

Wardrop's user equilibrium and system optimum traffic assignment principles were investigated considering the two route scenario. The effect of autonomous vehicle (AVs) fleets on the Volume Delay Function (VDF) was taken into consideration by creating a modified version of the traditional VDF according to the penetration of AVs in the traffic system. It was confirmed that the average travel time of the system optimum is shorter than that of the user equilibrium principle applying identical traffic demands. Moreover, the presence of AVs does not increase the maximum difference between the user and system optimum traffic assignment.
[LTH19, HLT+19]

This thesis presents the difference between the user-optimal and system-optimal traffic assignment by solving the classic two-route problem. The contribution of this thesis is different kinds of route attributes and the impacts of autonomous vehicle fleets on traffic assignment have also been examined. At last, the sensitivity analysis related to the road capacity is investigated.

The Wardrop equilibrium has been stated mathematically in several forms: the conceptually simplest form under the two route scenario is stated below as Eq. (11) and Eq. (12).

The user equilibrium principle can be stated in the following form:

$$\nu_1 = \begin{cases} d, & \text{if } d < \nu', \text{ where } T_1(\nu') = T_{0_2}, \\ \nu_s, & \text{otherwise, where } T_1(\nu_s) = T_2(d - \nu_s), \end{cases} \tag{11}$$

where $T_{0_1} \leq T_{0_2}$ is assumed. d is the total demand. $T_1(\nu)$ and $T_2(\nu)$ are the travel time of link 1 and link 2. ν_1 is the assigned flow volume in link 1. T_{0_1} and T_{0_2} are the free flow travel time of link 1 and link 2. The assigned volume in link 2 can be obtained by the constraints that $\nu_1 + \nu_2 = d$.

The system optimal principle can be stated as the following form:

$$\min[\nu_1 \cdot T_1(\nu_1) + \nu_2 \cdot T_2(\nu_2)] \tag{12}$$

subject to $\nu_1 + \nu_2 = d$, and $\nu_1, \nu_2 \geq 0$ [Pig13].

In addition to Eqs. (11-12) the travel time parameter must be investigated. In practice, the so-called Volume Delay Function (VDF) is used to calculate the link delays as a function of link volume in traffic assignment methods. US Bureau of Public Roads (BPR) developed a VDF in 1964, as shown in Eq. 13, which is a well-known formula to determine the travel time in each utilized link [BoPR64].

$$T(\nu) = T_0 \cdot [1 + \alpha \cdot (\frac{\nu}{c})^{\beta}], \tag{13}$$

where T is the travel time (minute), T_0 is the free flow travel time (minute), ν is traffic volume (passenger car unit (PCU) / hour), c equals the practical capacity (PCU/hour), and α, β are dimensionless parameters. For urban local traffic networks, α, β were calibrated for practical use as 6.6 and 3.9, respectively [JLC06].

The effect of autonomous vehicles (AVs) fleets on the VDF was taken into consideration as the next step in the research. The traditional VDF can be reformed considering the penetration of AVs in the traffic system. The BPR volume delay function was restated by [TSUV20] as follows:

$$T(\nu) = T_0 \cdot [1 + \alpha \cdot (\frac{\nu \cdot AV_{PCU}}{c})^{\beta}] + CF_k. \tag{14}$$

In this research, Wardrop's user equilibrium and system optimum traffic assignment principles were investigated considering the two route scenario. The results show that the average travel time of the system optimum is shorter than that of the user equilibrium principle applying identical traffic demands. Obviously, the system optimum principle makes the transportation system perform better, even though it may introduce unfairness to the passengers because the average travel time may not always be equal. This problem can be solved by rewarding the ones who take a longer time. The calculation results demonstrated that Wardrop's two principles are equivalent if the network has the same free flow travel time on each route. When the same type of routes has identical marginal travel time, they have the same average travel time. Moreover, the example calculations show that the autonomous vehicle fleets running in the traffic system will dramatically drop the average travel time on both routes. Even though the implementation of autonomous vehicle fleet on the traffic system does not enlarge the maximum difference between the user equilibrium and system optimum traffic assignment, the difference between the user equilibrium and system optimum is delayed and prolonged at the same time. This benefits from the improvement of road capacity when pure autonomous vehicle fleets drive on the road network.

In conclusion, the sensitivity analysis regarding the road capacity showed that the increase in capacity enlarges the difference between user equilibrium and system optimum by prolonging the different ranges. The work was carried out in a simple traffic network, but in the future, the equilibrium problem will be solved for a larger network and considering further parameters in a sensitivity analysis.

Thesis 4

A dynamic Deterministic Social Optimum (DSO) routing methodology has been elaborated by dynamic marginal travel time pricing to optimize the road's utilities. Three modes of traffic assignment were realized and compared. Compared with Stochastic User Equilibrium (SUE), DSO has considerable advantages in terms of reducing trip duration, time loss, waiting time, and departure delay under the same travel demand. The SUE traffic assignment has a more dispersed vehicle density distribution. DSO traffic assignment implicates that the occurrence of excessive congestion can be significantly reduced. By comparing the results of the UE and SO simulations, there are several tiny benefits in SO traffic assignment method. The difference of density distribution between UE and SO can also be ignored in the simulated network.
[TL19, LTH19, LT21b]

As a potential traffic assignment method for future transport with automated vehicles, the deterministic system optimum (DSO) is modeled and simulated to investigate the potential changes it may bring to the existing traditional traffic system. In this thesis, stochastic user equilibrium (SUE) is used to simulate the conventional traffic assignment method. By comparing the two simulation results, one can see the difference between the two traffic allocation modes. DSO has considerable advantages in reducing trip duration, time loss, waiting time, and departure delay under the same travel demand. The SUE traffic assignment has a more dispersed vehicle density distribution. Moreover, DSO traffic assignment helps the maximum vehicle density of each alternative path arrive almost simultaneously. Furthermore, DSO can significantly reduce or avoid the occurrence of excessive congestion.

In VDF, the v/c ratio can be larger than 1, which is impossible by considering the definition of road capacity. Consequently, the flow volumes applied in the macroscopic assignment are not rigidly referred to as the physically measured flows. The flow used in the VDF is treated more like a demand flow, which becomes delayed if it exceeds capacity. As a result, the VDF cannot be evaluated directly from the actual field measurements. [KD17] proposed a technique to overcome this problem by replacing the traffic flow with the traffic density [PCU/km]. They estimate the VDF by using density instead of flow. The formula is then straightforwardly reset as:

$$T(k) = T_0 \cdot [1 + \alpha \cdot (\frac{k}{k_c})^{\beta}]. \tag{15}$$

Here, k is the traffic density. k_c is the critical density at which the maximum flow occurs. α and β are tuning parameters, similarly as used in Eq. (13).

The difference between UE and SO is accounted for by the individual user's failure to share the cost he/she contributes to the total travel cost. The theoretical background of congestion pricing relies upon the marginal-cost pricing (or the first-best pricing) principle, which states that a toll equals the difference between the marginal social cost and the private cost to optimize the social surplus. The marginal travel cost of a link a at the flow $T_a^{'}$ is defined as the increase in total travel cost on the link a caused by an additional traveler. The difference between private and social costs is $T_a^{'}(k_a) \cdot k_a \cdot l_a$ [Pat15]. In order to achieve economic efficiency, every traveler must be made aware of the costs he/she imposes on other travelers. In this way, the traveler is supplied with an incentive to minimize social costs. Any SO problem may be solved as a UE problem by redefining travel costs as $C_a = T_a + T_a^{'}(k_a) \cdot k_a \cdot l_a$ [Pat15]. The first derivative of the travel time model (Eq. (15)) is

$$\frac{dT}{dk} = \frac{T_0 \alpha \beta}{k_c l} (\frac{k}{k_c})^{\beta - 1} \tag{16}$$

Thus, the SO marginal cost pricing becomes:

$$P(k) = k \cdot l \cdot \frac{dT}{dk} = T_0 \cdot \alpha \cdot \beta \cdot l \cdot (\frac{k}{k_c})^{\beta} \tag{17}$$

Here, $T(k)$ is the travel time, which is the user equilibrium pricing. $k \cdot l \cdot dT/dk$ is the marginal travel time the inserted vehicle incurred. l is the length of the road.

As shown in Fig. 3, an artificial road network with three alternative roads was used to verify the proposed dynamic link-based marginal cost pricing strategy validity. There was one pair of origin and destination. The origin edge was 400 meters long. At the end of it is 100 meters of connecting road. Three alternative routes converged the connection edge and their joint ends. At this intersection, a traffic signal light was equipped to regulate the traffic. The intersection was connected to the destination with an edge. At the start point of the destination, there was an intersection where another traffic light (traffic light 2) was located. A dummy edge was introduced to equip the

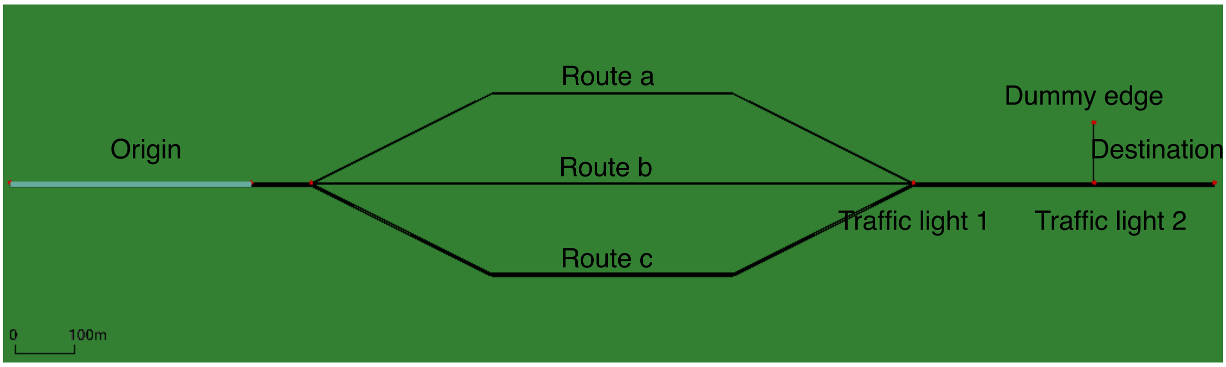

Figure 6: Simulation traffic network

traffic light. A variable speed signal (VSS) was applied to the destination. Traffic light 2 and the VSS were used to simulate the downstream traffic conditions. Except for route a, route b, and the dummy route, all edges have two lanes.

In this chapter, three traffic assignment models have been investigated to explore the possible advantages of deterministic social optimum traffic assignment over the stochastic user equilibrium assignment and deterministic user equilibrium. The newly introduced modified VDF was used to calculate travel time and marginal travel time. The system optimal assignment method of marginal travel time is realized by using the model. A simple fork road network was created using SUMO. In this model, three modes of traffic assignment were realized. By comparing the results of the DSO and SUE simulations, the possible benefits of deterministic SO were found. This study found that DSO has considerable advantages in terms of reducing trip duration, time loss, waiting time, and departure delay under the same travel demand.

What is more, the stochastic UE traffic assignment has a more dispersed vehicle density distribution. Moreover, deterministic SO traffic assignment helps the maximum vehicle density of each alternative path arrive almost simultaneously. Last but not least, SO can significantly reduce or avoid the occurrence of excessive congestion.

By comparing the results of the UE and SO simulations, there are several tiny benefits in SO traffic assignment method. The improvements of SO traffic assignment is merely 1 to 3 percentage in average trip duration, time loss, and, waiting time. The difference in density distribution between UE and SO can also be ignored in the simulated network.

Therefore, eliminating the uncertainty of road choice may improve the capacity of road network significantly. However, the benefits of SO over UE is not obviously in this three routes networks. The drawback of the present study is that the network is simple. A complex network should be needed to investigate the benefits of SO over UE in the fiture.

4 Future work

The planned future research concerns the results of Thesis 4: the control method is proposed and valid now for the small road network. The next topic includes extending the control method for more complex networks and examining the efficiency of the controlled transport. Then the mechanism of the control method must be carried out and popularized its application.

References

[BMW56] M. Beckmann, C.B. McGuire, and C.B. Winsten. Studies in the economics of transportation. Technical report, 1956.

[BoPR64] US Bureau of Public Roads. *Traffic assignment manual for application with a large, high speed computer*, volume 2. US Department of Commerce, Bureau of Public Roads, Office of Planning, Urban Planning Division, 1964.

[CB12] Malachy Carey and Michael Bowers. A review of properties of flow–density functions. *Transport Reviews*, 32(1):49–73, jan 2012.

[CTV15] A. Csikós, T. Tettamanti, and I. Varga. Macroscopic modeling and control of emission in urban road traffic networks. *Transport*, 30(2):152–161, 2015.

[D$^+$79] P.D.C. Dow et al. Capacity-restrained road assignment. *Traffic Engineering & Control*, 20(6), 1979.

[Dag07] C.F. Daganzo. Urban gridlock: Macroscopic modeling and mitigation approaches. *Transportation Research Part B: Methodological*, 41(1):49–62, 2007.

[Fri16] B. Friedrich. The effect of autonomous vehicles on traffic. In *Autonomous Driving*, pages 317–334. Springer, Berlin, Heidelberg, 2016.

[God69] J.W. Godfrey. The mechanism of a road network. *Traffic Engineering & Control*, 8(8), 1969.

[JLC06] Mansoureh Jeihani, Stephen Lawe, and JP Connolly. Improving traffic assignment model using intersection delay function. Technical report, 2006.

[KD17] Rafał Kucharski and Arkadiusz Drabicki. Estimating macroscopic volume delay functions with the traffic density derived from measured speeds and flows. *Journal of Advanced Transportation*, 2017, 2017.

[KEPP14] M Keyvan-Ekbatani, M. Papageorgiou, and I. Papamichail. Perimeter traffic control via remote feedback gating. *Procedia-Social and Behavioral Sciences*, 111:645–653, 2014.

[KTSH08] A. Kesting, M. Treiber, M. Schönhof, and D. Helbing. Adaptive cruise control design for active congestion avoidance. *Transportation Research Part C: Emerging Technologies*, 16(6):668 – 683, 2008.

[MWH87] H Mahmassani, James C Williams, and R Herman. Performance of urban traffic networks. In *Proceedings of the 10th International Symposium on Transportation and Traffic Theory*, pages 1–20. Elsevier Amsterdam, The Netherlands, 1987.

[New93] G.F. Newell. A simplified theory of kinematic waves in highway traffic. *Transportation Research Part B: Methodological*, 27(4):281 – 313, 1993.

[ORAA18] A. Olia, S. Razavi, B. Abdulhai, and H. Abdelgawad. Traffic capacity implications of automated vehicles mixed with regular vehicles. *Journal of Intelligent Transportation Systems*, 22(3):244–262, 2018.

[Pat15] Michael Patriksson. *The traffic assignment problem: models and methods*. Courier Dover Publications, 2015.

[Pig13] Arthur Cecil Pigou. *The economics of welfare*. Palgrave Macmillan, 2013.

[PT19] G. Pauer and Á. Török. Static system optimum of linear traffic distribution problem assuming an intelligent and autonomous transportation system. *Periodica Polytechnica Transportation Engineering*, 47(1):64–67, 2019.

[SABB17] K. Sjoberg, P. Andres, T. Buburuzan, and A. Brakemeier. Co-operative intelligent transport systems in europe: Current deployment status and outlook. *IEEE Vehicular Technology Magazine*, 12(2):89–97, 2017.

[TM16] A. Talebpour and H.S. Mahmassani. Influence of connected and autonomous vehicles on traffic flow stability and throughput. *Transportation Research Part C: Emerging Technologies*, 71:143 – 163, 2016.

[TME17] A. Talebpour, H.S. Mahmassani, and A. Elfar. Investigating the effects of reserved lanes for autonomous vehicles on congestion and travel time reliability. *Transportation Research Record: Journal of the Transportation Research Board*, 2622:1–12, 2017.

[TSUV20] Árpád Török, Zsolt Szalay, Gábor Uti, and Bence Verebélyi. Modelling the effects of certain cyber-attack methods on urban autonomous transport systems, case study of budapest. *Journal of Ambient Intelligence and Humanized Computing*, 11(4):1629–1643, 2020.

[TVS16] T. Tettamanti, I. Varga, and Zs. Szalay. Impacts of autonomous cars from a traffic engineering perspective. *Periodica Polytechnica Transportation Engineering*, 44(4):244–250, 2016.

[VAVDV06] B. Van Arem, C.J.G. Van Driel, and R. Visser. The impact of cooperative adaptive cruise control on traffic-flow characteristics. *IEEE Transactions on Intelligent Transportation Systems*, 7(4):429–436, 2006.

[WMIH87] James C Williams, Hani S Mahmassani, S Iani, and Robert Herman. Urban traffic network flow models. *Transportation Research Record*, 1112:78–88, 1987.

Publications of the Author

[HLT+19] M.T. Horváth, Q. Lu, T. Tettamanti, Á. Török, and Zs. Szalay. Vehicle-In-The-Loop (VIL) and Scenario-In-The-Loop (SCIL) automotive simulation concepts from the perspectives of traffic simulation and traffic control. *Transport and Telecommunication Journal*, 2(20):153–161, 2019.

[LT18] Q. Lu and T. Tettamanti. Impacts of autonomous vehicles on the urban fundamental diagram. In *5th International Conference on Road and Rail Infrastructure, CETRA 2018,*, pages 1265–1271, 17-19. May 2018.

[LT21a] Q. Lu and T. Tettamanti. Impacts of connected and automated vehicles on freeway with increased speed limit, international journal of simulation modelling. *International Journal of Simulation Modelling (IJSIMM)*, 2021.

[LT21b] Q. Lu and T. Tettamanti. Traffic control scheme for social optimum traffic assignment with dynamic route pricing for automated vehicles. *Periodica Polytechnica ser. Transportation Engineering*, 2021.

[LTH19] Q. Lu, T. Tettamanti, and D. Hörcher. Implications of user and system optimum based traffic control considering autonomous fleets. In *2019 IEEE International Conference on Connected Vehicles and Expo (ICCVE)*, pages 1–5, 2019.

[LTHV20] Q. Lu, T. Tettamanti, D. Hörcher, and I. Varga. The impact of autonomous vehicles on urban traffic network capacity: an experimental analysis by microscopic traffic simulation. *Transportation Letters*, 12(8):540–549, 2020.

[MLT19] B. Maximcsuk, Q. Lu, and T. Tettamanti. Determining maximum achievable flows of autonomous vehicles based on macroscopic fundamental diagrams. *Perner's Contacts, Special Issue: "36th International Colloquium on Advanced Manufacturing and Repair Technologies in Vehicle Industry"*, pages 192–199, 2019.

[TL19] T. Tettamanti and Q. Lu. *Lecture Notes on Control Theory.* Akadémiai Kiadó, 2019.