Urban Traffic Congestion Alleviation Relying on the Vehicles' On-board Traffic Congestion Detection Capabilities*

Zoltán Fazekas[1], Mohammed Obaid[2], Lamia Karim[3] and Péter Gáspár[1,4]

[1] HUN-REN Institute for Computer Science and Control (HUN-REN SZTAKI), Kende u. 13-17, H-1111 Budapest, Hungary, {zoltan.fazekas, peter.gaspar}@sztaki.hun-ren.hu

[2] Department of Automotive Technology, Faculty of Transportation Engineering and Vehicle Engineering, Budapest University of Technology and Economics, Stoczek u. 6, H-1111 Budapest, Hungary; obaid.mohammed@mail.bme.hu

[3] National School for Applied Sciences (ENSA), Hassan First University of Settat, Avenue de l'université, B.P. 218, Berrechid, Morocco; lamia.karim@uhp.ac.ma

[4] Department of Control for Transportation and Vehicle Systems, Faculty of Transportation Engineering and Vehicle Engineering, Budapest University of Technology and Economics, Stoczek u. 2, H-1111 Budapest, Hungary; gaspar.peter@kjk.bme.hu

*This work is dedicated to the memory of Prof. Azedine Boulmakoul, a dear friend and an excellent colleague from Morocco.

Abstract: Traffic simulation experiments were carried out for an urban road network to explore the effect of road vehicles' individual traffic congestion avoidance efforts, in which on-board visual line-of-sight (LoS) exteroceptive sensors (ECSs) and related on-board traffic congestion detection (OTCD) capabilities are put to use on the network level traffic situation. OTCD requires a visual LoS constellation between the subject vehicle and some vehicles in the vehicle queue ahead. The experiments concern themselves with the comparison of undisturbed, disturbed and mitigated traffic. PTV Vissim traffic simulator was used in the experiments. The process of congestion detection, avoidance and mitigation was tentatively modelled via proxy parameters. Two series of experiments are reported herein. A new approach to route planning has been identified and earmarked for future research.

Keywords: traffic simulation; traffic congestion; driver assistance systems; exteroceptive sensors; route planning

1 Introduction

Intelligent road vehicles (IRVs) with their advanced driver assistance systems (ADAS), on-board smart sensors, navigational and info-communication devices have already become part of everyday life in many countries worldwide. Autonomous road vehicles (AVs) have yet to achieve such prevalence [1].

Many of the automotive sensors that appear in, or on-board IRVs and AVs are visual line-of-sight (LoS) sensors. Sensors of this kind can detect obstacles, vehicles, road objects, humans, animals, etc. that they can actually 'see', or in other words, that are in the sensors' visual LoS regions. Mono and stereo cameras, infrared cameras, LIDARs, and radars are exemplars of such sensors. Some of the automotive LoS sensors look within the subject vehicle, in this sense these sensors are proprioceptive sensors, while others, i.e., the ones looking out of the subject vehicle, are exteroceptive sensors (ECSs). In-depth reviews of LoS sensors and their typical applications in vehicular measurements are given in [2-4].

1.1 Mottos and Conjectures

Three relevant quotes are included here as mottos, from [5-7]:

The first motto:

> *'Road accidents and traffic congestion are two critical problems for global transport systems. Connected vehicles and automated vehicles are among the most heavily researched and promising automotive technologies to reduce road accidents and improve road efficiency. However, both automated vehicle and connected vehicle technologies have inherent shortcomings, for example, line-of-sight sensing limitation of automated vehicles' sensors and the dependency of high penetration rate for connected vehicles.'*

The second motto:

> *'Autonomous systems should be designed with the ability to produce several alternative ways to complete their tasks …*
> *… the system should not only be able to find alternative routes when it encounters traffic jams and blocked roads. If the system realizes that it cannot complete its mission, it should be programmed to transfer the passenger to another mode of transportation – such as taking them to a train station …'*

The third motto:

> *'For geometric design [of roads], the most useful form of classification is functional classification, as it defines the spectrum of road usage from pure mobility to pure accessibility. This, in turn, supports the selection of the design speed and the design vehicle. These two parameters, in combination with current and anticipated traffic volumes, define geometric standards of horizontal and vertical alignment, and intersections or interchanges and definition of the cross-section.'*

As pointed out in the first motto, road accidents and traffic congestion are critical problems for transport systems. Statistical data on serious and fatal road accidents, see [8], keep frustrating transport stakeholders and common road users worldwide alike. Beside accidents, urban traffic congestion has many other detrimental effects, and these manifests themselves at different scales of the society and economy [9]. Three conjunctures/hypotheses for the present study are included below; the first one logically links road accidents and urban road traffic congestion.

> **Conjecture 1:** A high proportion of serious and fatal accidents occurs in urban areas at times of traffic congestion. Any decrease in accident numbers associated with traffic congestion is likely to lessen also the total figures of serious and fatal accidents.

Motivated also by the above conjecture, ways are sought worldwide to better understand and reduce urban road traffic congestion. To this end, road traffic simulation experiments were carried out – in the frame of the study presented herein – for an urban subnetwork to explore the joint effect of road vehicles' individual rational traffic congestion avoidance efforts. The simulation experiments were de-signed to model traffic congestion that forms due to some unexpected, non-recur-ring traffic incident. As in such cases, the incident itself and the forming congestion remain unreported for some time, typically for some minutes, the deteriorating traffic situation necessitates the application of local congestion detection, avoidance and alleviation approaches. One such approach, proposed in [10], relies on dedicated sensors and enhanced vehicle detection capabilities that are available on-board the road vehicles moving in the traffic, and perceive the build-up of vehicle queues in the vicinity. This approach is revisited herein and the effect of certain parameters are looked at in some detail.

> **Conjecture 2:** Visual LoS exteroceptive sensors – on-board vehicles – and their supporting on-board traffic congestion detection (OTCD) systems could and should play an important role in urban road traffic congestion alleviation, at least locally, and especially before:
>
> a) Network-level traffic congestion alleviation interventions are initiated
>
> b) The effect of these interventions is felt in the road network, and also locally.

Such sensors and such OTCD capabilities – either artificial, or human – on-board vehicles participating in the urban road traffic were assumed and considered in the simulation experiments mentioned above. The experiments concern themselves with the comparison of undisturbed, disturbed and mitigated road traffic.

The local traffic conjunction mitigation approach used herein led to considerable traffic improvements in a number of cases, however, such an improvement cannot always be guaranteed. This is phrased as a conjecture below.

Conjecture 3: Not all urban traffic situations/incidents can be handled, not all transport assignments/missions can be supported by the application of local traffic congestion detection, avoidance and alleviation approaches.

To prove the truth of Conjecture 3, a fairly common, but sensitive transport assignment/task – along an important urban route – is considered. The traffic along the route is strongly hindered by a possibly minor traffic incident. It turns out that the adverse traffic situation formed cannot be promptly resolved, and so the commenced transport task cannot be accomplished via the application of local traffic congestion avoidance and alleviation approaches.

In order to properly tackle similar sensitive transport assignments/tasks, a new objective for route planning and optimization is proposed herein. The route planning and optimization that considers also this new objective should be studied and further researched as it could attract interest from the military, police, and security fields, and find applications in such missions and routing tasks, as well as in fairly common, ordinary routing tasks.

1.2 Modelling Traffic That Involves Vehicles with Vehicle-Queue Detection Capabilities

The disturbance brought about to the urban road subnetwork under study is a sudden, unexpected and non-recurring, possibly minor traffic incident that causes vehicle queues and traffic congestion in the area. The drivers/AVs – relying on their own LoS ECSs and OTCD capabilities – see/detect the traffic queues in the congested area, and try to avoid them. This detection requires an LoS constellation between the subject vehicle/driver and at least some of the vehicles stuck in the queues ahead. The intention to avoid the congested road sections and the resulting re-routing of the vehicles affect the traffic flow in the area and to some extent mitigate the traffic congestion.

Traffic simulation experiments were carried out to model the above outlined complex spatio-temporal process. It, however, was modelled – for reasons given in Section 2.2 – in a simplified way. Two series of traffic simulation experiments, referred to as case studies, concerning the subnetwork were carried out and their simulation results are reported herein. These experiments continue and extend those described in book chapter [10]. Indeed, the urban road subnetwork analyzed herein is the same as one of the three road subnetworks analyzed in the cited book chapter, however, the traffic conditions, namely the obstacle locations, and/or some parameters used in the simulations do differ.

Furthermore, in the cited book chapter, strong emphasis was put on the alternatives of OTCD based traffic mitigation approach, in particular, on the various communication means, channels, services and options that help drivers/AVs to keep away from congested urban areas. These alternatives were found superior – on a network-level – to OTCD based traffic congestion mitigation, particularly for highly developed urban areas, and after an initial delay. However, application niches and target user groups for OTCD systems were identified in book chapter.

Accepting the conclusions drawn in [10], the focus of the present study is to answer the following questions.

- What happens to the traffic if car drivers/AVs still use the aforementioned individualistic traffic congestion avoidance approach?
- Do the OTCD based individual congestion avoidance efforts add up and alleviate traffic congestion in the area?
- What happens to the traffic elsewhere in the road subnetwork?

Clearly, sharing information on detected vehicle queues via available communication channels/infrastructure is an excellent way forward in network-level traffic congestion mitigation, but again this is applicable only in highly developed urban areas, see [11]. Herein, however, these communication possibilities are set aside, but the general approach of decentralized traffic congestion control – advocated in the above cited article – is followed.

1.3 Further Related Literature

One way of dealing with urban road traffic congestion is building new roads and improve the transport infrastructure and related communication facilities, and transport services in general. For various reasons, e.g., for economic, architectural, geographic, topographical reasons, this way of improving the traffic situation might not be possible. In such cases, alternative traffic congestion mitigation measures are required.

The spread of AVs is usually deemed beneficial also for easing traffic congestion, see e.g., [12]; nevertheless, according to [13], the urban transportation infrastructure needs to be ready for the sustainable deployment of AVs. The author opines that a key aspect of this readiness is to introduce certain modifications in road design and adjust traffic control accordingly. The author investigated the adjustments needed for interrupted traffic flow, and modelled the altered circumstances and conditions using the PTV Vissim traffic simulator [14] [15]. Results published in [13] indicate that even if the recommended modifications are fully adhered to and properly implemented, AVs alone, i.e., without connectivity features, do not improve the capacity of the road network considerably. Simulation results presented in [12], on the other hand, show that the capacity of an urban road network increases quasi-linearly with AV-penetration; maximum traffic flow, for instance, increased by 25% as the mentioned parameter was changed from 0% to 100%.

The authors of [16] opine that the study of OTCD capabilities have been neglected in the literature. One of the reasons for this disinterest could be that visual detection of vehicle-queues in the vicinity is easy for experienced and/or local drivers, but it is quite challenging to devise, formulate, implement and validate reliable real-time OTCD algorithms that can be deployed in ADAS/AD subsystems. In contrast to this disinterest, a considerable number of traffic congestion detection methods and systems that rely on data from static traffic sensors were reported during the last decade, e.g., [17] [18]. Several of the methods and systems proposed in this period make use of artificial intelligence. It is quite likely that some of these methods and systems are adaptable for the tasks of OTCD based avoidance and mitigation. Another reason for the mentioned disinterest is that in the era of advanced vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications [19] [20], communication-based solutions are serious rivals to OTCD systems.

In case of AVs, the OTCD capability should technically build upon some more common LoS detection capabilities provided by certain ADAS/AD subsystems and functions onboard. The research on such – in the present context subordinate – detection capabilities is reviewed in [21].

Two frameworks presented therein are relevant for the present study. The first one concerns traffic conflict-based vehicle intelligence, while the second one is a cooperative control framework. Both frameworks refer to tasks, subsystems and capabilities, e.g., detection of traffic participants and nearby obstacles, managing travel information, making use of the vision, radar and multi-sensor fusion subsystems, predicting traffic conflicts and escaping/avoiding the more serious ones, which are related to the present topic. Escaping unexpected incidents, or even disasters, by autonomous systems, such as AVs, was the topic of [6] from which our second motto has been borrowed. The authors of the cited paper argue that despite the unpredictability of such events, handling of the arising situations is often possible.

According to [22], numerous traffic simulators were developed in the last decades. In conjunction with study described in [13], the Vissim traffic simulator has been already mentioned. For the traffic simulation experiments presented herein, also this traffic simulator was chosen[1] and used. Vissim microscopic traffic simulator [14] [15] runs different simulation factors and parameters at a complex microscopic level, and runs the simulation with high number of iterations until achieving near real-life conditions. It can handle both real and user defined maps to study a number of different conditions. It is often the simulator of choice for real road networks [26] as it can run complex equilibrium assignments.

[1] When taking this decision, also the planned application of Vissim-MATLAB cooperation via the COM interface, see [23-25], was considered. See details in Subsection 2.2.

The network-level benefits of navigation and route guidance systems (NRGSs) used by drivers/vehicles were assessed in [27]. In the traffic simulations presented therein, such systems were used and relied on by growing proportions of drivers/ vehicles. The authors compared total travel times, as well as total delays within the road network for eleven different parametrized sub-scenarios (PSSs.)

In the simulations presented in [28], the authors used Vissim's Dynamic Traffic Assignment (DTA) simulation option [15]. The PSSs drawn on in their assessment were parametrized by the percentage of the traffic demand equipped with NRGSs. According to [28], there are several benefits of employing DTA in simulations. However, they opine that it makes the simulation task more complex, furthermore, it necessitates additional parametrization, calibration and validation of the model.

Due to the lack of built in LoS filtering support in the commonly used versions of the Vissim, the complex process of vision-based traffic congestion detection and avoidance presented herein was tentatively modelled via proxy parameters. A similar proxy-based modelling approach was taken in [23] [24] regarding the utility assessment of a driver assistance system and the effectivity of a traffic control, respectively.

1.4 Scope and Structure of The Manuscript

The joint effect of the individual OTCD capabilities is assessed in the simulation-based experiments presented herein. The question of how such artificial capabilities can be reached and implemented has not been addressed herein, but clearly such capabilities are within the reach of the present-day, leading-edge automotive technology [3]. The simulation experiments concern themselves with the undisturbed, disturbed and mitigated traffic within an urban road subnetwork. Even though the traffic is modelled in a simplified way, experimentation with the proxy parameters helps to understand their roles, and relates some of them to the urban texture, see [29].

The rest of the manuscript is organized as follows. Section 2 presents the simulation experiments concerning the OTCD based urban traffic congestion mitigation. In Subsection 2.1, the simulation environment is briefly described. Then, in Subsection 2.2, the simulation approach is presented and justified. In Subsection 2.3, the target road subnetwork is introduced. In Section 3, two case studies concerning unexpected traffic congestions are included. The first case study is presented in Subsection 3.1, while the second in Subsection 3.2. The results of the simulation experiments are discussed in Subsection 3.3. In Section 4, the sensitive transport assignment referred to in Subsection 1.1 is presented and discussed. In Section 5, conclusions are drawn and further research is suggested.

2 Traffic Simulation Based Experiments

2.1 The Simulation Environment

As it was mentioned earlier, Vissim simulator was chosen and used for the simulation experiments reported in the present study. The traffic models created in Vissim normally rely on its own generic traffic flow models. These characterize and describe vehicle movements both in longitudinal and lateral directions, moreover the model may include roads with different lane structures. The simulator has a number of traffic conflict resolution models, which can simulate and manage cross-roads, junctions and pedestrian crossings, as well as road locations with road layout changes. All these are road locations where traffic conflicts are likely to arise. Relying on Vissim's built in capabilities, one can build realistic road network models, and can obtain realistic simulation results. Still, it has its inherent limitations; and these need to be addressed when complex traffic schemes, unusual traffic aspects, out of the ordinary/vehicle functions, or new communication techniques/services are to be modelled and implemented.

2.2 The Simulation Approach

Currently, the generic versions of the Vissim simulator framework do not provide built in LoS filtering support for their users; or in other words, the visibility between vehicles/road users cannot be checked within a customary simulation, and so the visibility relation between vehicles/road users can not be used as a condition for an action, or decision. Such relations, however, could be approximated through and utilized in a Vissim-MATLAB cooperation. Albeit such an implementation would result in a more faithful modelling and simulation of the traffic that involves also vehicles with OTCD capabilities, it is left as a target for future work. This decision was taken with a view on the more involved and longer effort needed for Vissim-COM-based developments reported by both [23] [24]:

- A possible introductory move forward could involve semi-automatic generation and evaluation of LoS regions of the queues within a road subnetwork. The move could start with sampling the subnetwork either manually, or algorithmically, so that only a few hundred discrete road locations remain that still characterize the subnetwork properly.

The difference between the physical and the sampled road location-based visibility is illustrated via a simple example shown in Figure 1. Two vehicles wait in a queue that has formed because of a car crash near an urban road crossing. The figure shows that the last car in the queue is not in the visual LoS region of the purple car that approaches to the road crossing as a building blocks its view.

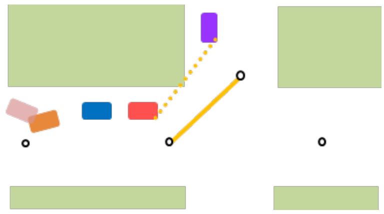


Figure 1
An example for which the sampled road location-based visibility and the vehicle based physical visibility do not coincide. The lack of the LoS connection is indicated by a dotted line, while the solid line indicates that the two sampled road locations are in LoS connection.

Though the physical visibility – in real road traffic – and the sampled road location-based visibility – in a restricted microscopic traffic simulation – provides information on whether a vehicle is present, or not, at the other, i.e., viewed, road location, it is not possible to deduce from this fact if there is a queue there, or not.

It was mentioned in Subsection 1.4 that the queue detection method implemented by the OTCD system is not addressed in the present manuscript, but its traffic simulation aspects should be touched upon:

- In a dedicated lane-based microscopic traffic modelling/simulation, some characteristic traffic descriptor (e.g., recent average vehicle speed in the lane) should be collected and calculated for the close vicinity of each discrete road location that has been sampled and chosen for assessing the visibility.
- In Vissim-based simulations, queue counters – associated with each of the aforementioned discrete road locations – should be introduced and used for the purpose of detecting queues from a distance.

In the tentative approach used herein, however, the intricate spatio-temporal process of traffic congestion detection and avoidance relying on individual OTCD capabilities is modelled and simulated in a much-simplified manner by using three proxy parameters. The first of these serve as a defining parameter of sub-scenarios, while the second and third represent specific time-delays.

The first proxy parameter – denoted by γ – falls in range of 0.0 to 1.0; and for convenience, is given in percentages. It is used for the purpose of quantifying the mitigation of the traffic hindrance that has been caused by some disturbance; more precisely, it specifies the percentage of the road vehicles equipped with and relying on their own OTCD systems among the vehicles. In the simulation experiments, these percentages represent the proportions of vehicles diverted from the blocked paths to other compatible paths. Proxy parameter γ also serves as a defining parameter of the sub-scenarios; γ was assigned different discrete values for these, namely 0%, 5%, …, 25%, and 30% (i.e., step of 5%)[2].

The second proxy parameter represents the time required for driving around the obstacle in the traffic, it is denoted by T_{stop} as it was implemented through vehicles' stopping at the obstacle; while the third proxy parameter represents the time required for taking a rerouting decision, and it is denoted by $T_{decision}$. Proxy parameter T_{stop} can be linked to the obstacle size relative to the road-width/lane-width, and also to the seriousness of the traffic incident, as well as to the traffic intensity; while $T_{decision}$ represents the time required for a driver/AV who/that has reached the vicinity of the obstacle to find that:

a) A vehicle queue has built up there, due to some unusual reason
b) This queue will not dissolve quickly
c) To establish – through his/her local knowledge, or by use of a navigation device – that one or more alternative route is available
d) The time required for the planning of the modified route, should also be included.

Choosing these time delays properly is a precondition of achieving a realistic estimation of the LoS based traffic congestion avoidance and mitigation process. If fixed time-delays are used in the simulation, then these delays can be estimated, e.g., by falling back onto some very simple traffic model. Another possibility would be to make use of real-life time measurements taken in different traffic conditions in the area close to the intended obstacle location. Alternatively, the intersections near the intended obstacle location could be looked at via focused microscopic traffic simulations to come up with realistic estimates for the delays. Plausible ad hoc choice is a further possibility. T_{stop} and $T_{decision}$ are used in the first case study as fixed time-delays; they, on the other hand, are varied in the second.

2.3 The Road Subnetwork Used in the Simulation Experiments

The subnetwork chosen for the simulation experiments is a subnetwork of roads in Budapest, Hungary. It is situated on the west bank of the River Danube. The Móricz Zsigmond Circus (MZSC) is in the center of the target subnetwork, as it is shown in Figure 2. The travel demands used in the simulations are artificial, but realistic. Each demand is associated with an ordered pair of numbered locations, i.e., with the origin (O) and destination (D) locations, within the

[2] Increasing γ beyond a limit, in this case beyond 30%, did not improve the traffic situation any further, and for this reason, the corresponding sub-scenarios are not includeed herein.

subnetwork. These O-D pairs are referred to as routes in the text, and are denoted as in Route 2→1.

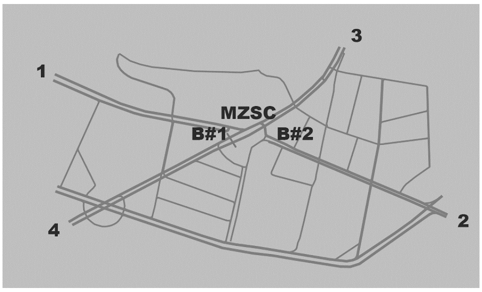


Figure 2
The modelled subnetwork of roads

In the map, four numbered locations are indicated; each of these generates and resorbs traffic to/from the other numbered locations, respectively. The lengths of shortest paths for Routes 2→1, 2→4, 3→4 are 2.4 km, 2.5 km and 1.5 km, respectively.

3 Traffic Simulation Case Studies

3.1 The First Case Study

The First Scenario (FS) of the First Case Study is looked at in Sub-subsection 3.1.1, the Second (Base) Scenario (SBS) in Sub-subsection 3.1.2, the PSSs of Second Scenario in Sub-subsection 3.1.3, and the Enroute Dynamic Rerouting (EDR) for Second Scenario in Subsubsection 3.1.4.

3.1.1 First Scenario: The Undisturbed Traffic

The FS specifies an undisturbed traffic – within the subnetwork shown in Figure 2 – without any hindrance:

- The subnetwork moves a total of 3600 vehicles between its four numbered road locations in an hour.
- A simulation run models a one-hour interval. Within this interval, vehicles are ‘generated’ only in the first 45 minutes, in the remaining 15 minutes the subnetwork is left on its own to discharge.
- Each of the four numbered location ‘generates’ equal number of vehicles, i.e., 300 vehicles, heading for each of the other three numbered road

locations within the simulated period, i.e., total travel demand D_{total} is 3600 vehicles/hour.

- Major junctions within the subnetwork are modelled as signalized junctions.

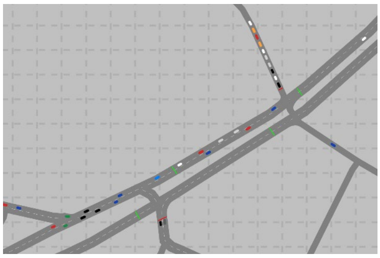


Figure 3
A snapshot of the undisturbed traffic according to the FS within a rectangular area at and near MZSC. The road vehicles appear as miniscule elongated color blobs.

The traffic that forms under the above conditions is not very intense, and is undisturbed, as can be perceived from the sub-image of a simulation snapshot shown in Figure 3. In Table 1, the average travel times (ATTs) on certain routes and corresponding numbers of arrived vehicles (NAVs) are shown. No recent traffic information is communicated to and used by the drivers/AVs modelled in this simulation run. The routes included in Table 1 – and also in Table 2 – are the ones that are to be hit hardest by the obstacle popping up according to SBS.

Table 1
The average travel times (ATTs) and the numbers of arrived vehicles (NAVs) per hour for the FS on two specific routes

Route	ATT [s]	NAV
$2 \rightarrow 4$	427	300
$3 \rightarrow 4$	160	300

Table 2
The ATTs and the NAVs per hour for the FS on two specific routes; however, in this case the drivers/AVs could make use of recent traffic information communicated to them

Route	ATT [s]	NAV
$2 \rightarrow 4$	545	267
$3 \rightarrow 4$	150	300

In Table 2, the ATTs and NAVs per hour are shown for the aforementioned routes. These traffic descriptors are also for the FS, however, in this case the drivers/AVs – modelled in the traffic simulation – had access to recent traffic information, which had been received by their NRGSs. Comparing the corresponding traffic descriptors presented in Tables 1 and 2, one can see that the utility of the recent traffic information – in case of undisturbed and calm traffic – is not distinct.

3.1.2 Second Base Scenario: An Obstacle Greatly Hinders the Traffic

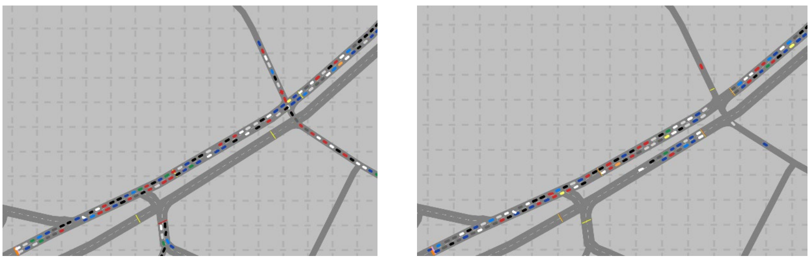
In the SBS, an obstacle pops up (e.g., bus breaks down) close to MZSC on the road that leads from MZSC to Location 4:

- The obstacle is modelled to stop each vehicle – passing it in the mentioned direction – for 60 s. In other words, T_{stop} is fixed, and is set to 60 s for the simulations implementing the SBS and the PSSs.

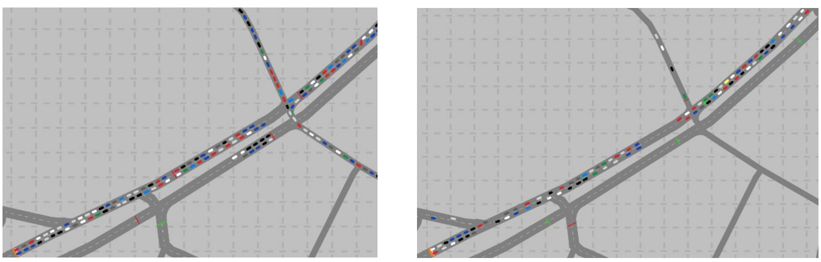
The full-blown effect of the obstacle's appearance in the road subnetwork on the traffic situation can be perceived by viewing Figure 4a. A continuous vehicle queue has formed on the road that leads from Location 3 to Location 4 – in this direction – in the road section shown in the figure.

3.1.3 Parametrized Sub-scenarios of the Second Scenario: Easing the Traffic Congestion via Vehicle Diversions to Compatible Alternative Paths

The second scenario has been split up into a number of PSSs based on proxy parameter γ.



(a) (b)



(c) (d)

Figure 4

The full-blown effect of the obstacle's appearance on the traffic (a). The traffic jam is then eased via diversions of 10% (b), 20% (c) and 30% (d) of the vehicles concerned.

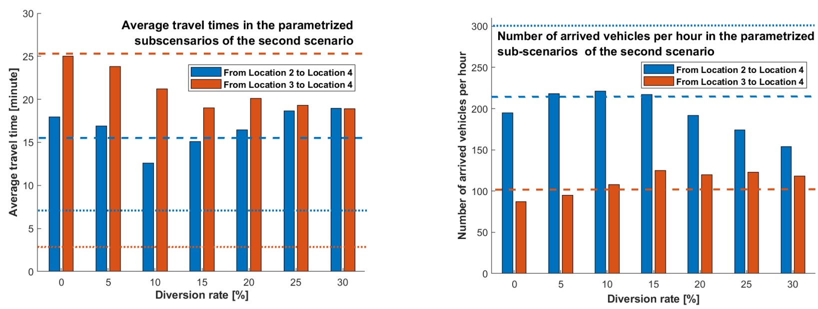
- The congestion is mitigated through diversions of growing proportions to alternative paths of the respective routes; seven discrete values of γ were used in separate simulation runs. In these, 0%, 5%, 10%, … , 25% and 30% (i.e., step of 5%) of vehicles were diverted with a sixty-second delay from the blocked path to alternative compatible paths, i.e., $T_{decision}$ is fixed, and set to 60s.

Simulation snapshots corresponding to four out of the seven aforementioned simulation runs have been included herein. The snapshots for PSSs corresponding to 0%, 10%, 20% and 30% (i.e., step of 10%) vehicle diversions[3] are shown in the subfigures of Figure 4.

Diagrams presented in Figure 5 show the ATTs and NAVs per hour, respectively, for vehicles travelling along Routes 2→4 and 3→4 according to the PSSs. The diagrams indicate that certain diversions, namely the 10% and the 15% ones, have perceptively eased the traffic situation on these "hard hit" routes, respectively.

3.1.4 Easing the Traffic Congestion of the Second Base Scenario via EDR

In the simulation experiments reported in this subsubsection, the effect of traffic congestion mitigation via EDR is looked at. Unlike the more detailed study presented in [27], herein the percentage of the vehicles equipped with NRGSs has not been varied in fine grades, rather either all the drivers/AVs made use of NRGSs, or none of them did.



(a) (b)

Figure 5

The effect of EDR – making use of recent road traffic information – and of the PPSs on ATTs (a) and on NAVs per hour (b) for Routes 2→4 and 3→4 for the second scenario. Dashed lines indicate ATTs and NAVs, respectively, for the second scenario with EDR, while the dotted lines indicate these traffic descriptors for the undisturbed traffic, i.e., for FS.

3 Note that the case of γ = 0%, is actually the SBS.

The benefit of receiving recent traffic information about the road network – via NRGSs – is assessed herein based on two specific traffic descriptors, namely a) ATTs, and b) NAVs per hour, calculated for two selected routes, namely for Route 2→4 (blue[4]) and Route 3→4 (red), of the subnetwork:

- The aforementioned traffic descriptors computed for the undisturbed traffic – without and with EDR, see Tables 1 and 2, respectively – have already been looked at, and compared. Based on this comparison, one can see that EDR – relying on recent traffic information received via NRGS – is not particularly useful in case of undisturbed traffic, as the traffic flows smoothly anyway.
- On the other hand, in the congested traffic that builds up according to the SBS, EDR– making use of recent traffic information – may considerably improve the traffic situation[5]. This improvement reveals itself also in the traffic descriptors mentioned above; these are shown diagrammatically in the respective subfigures of Figure 5.

3.2 The Second Case Study

In the present subsection, the simulation experiments presented in [10] – in respect of using individual OTCD capabilities for traffic congestion detection and alleviation – are reiterated. More concretely, all the parameters defined earlier, i.e., γ, T_{stop}, and $T_{decision}$, will be varied. Moreover, in some of the experiments, also parameter D_{total}, which specifies the total travel demand in the target subnetwork, will be varied. T_{stop}, $T_{decision}$ and D_{total} are varied around their respective fixed values considered in the first case study. By varying these, the aim was to better understand their roles in the model, to delimit the spatio-temporal process of congestion detection and avoidance based on OTCD capabilities.

The present subsection is structured as follows. Subsubsection 3.2.1 presents the FS, in which the undisturbed road traffic within the target subnetwork is examined; then, in Subsubsection 3.2.2, the SBS and PSSs are examined.

3.2.1 First Scenario with Different Total Travel Demands

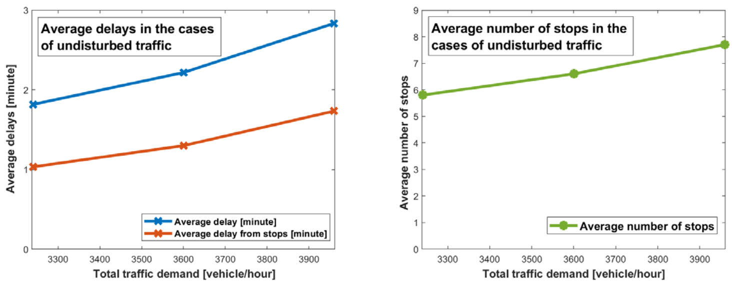
In this subsubsection, the undisturbed road traffic in the subnetwork shown in Figure 2 is looked at under three different total travel demands. More concretely:

4 The traffic descriptor values for Route 2→4 are shown as blue bars in the subfigures of Figure 5, whereas the descriptor values for Route 3→4 are shown as red bars there.

5 The improvement achieved through EDR is less though than that achieved by the best of the parametrized sub-scenarios (see Figure 5). Please recall that these sub-scenarios serve as proxies for the modelled OTCD based traffic congestion alleviation approach.

- The traffic that takes shape under 90%, 100% and 110% of D_{total} used in the first case study are looked at. There, D_{total} was chosen to be 3600 vehicles/hour. Each of these total travel demands is divided equally between the twelve considered routes, and the distribution of the travel demands in time – within each simulation run – is the same as it was in the first case study.

Figures 6 and 7 present diagrams of four specific traffic descriptors. In Figure 6a, the average delays (blue) and average delays due to stops (red) experienced by drivers/AVs travelling in the subnetwork are shown. The tendency of these delays matches the intuition: with higher traffic demands these delays grow.



(a) (b)

Figure 6
The average delays and the average delays from stops (a) and the average number of stops (b) – within the undisturbed traffic – for various traffic demands

Figure 6b presents the average number of stops drivers/AVs had to make during their travel through the subnetwork because of the other vehicles and of the traffic signals. The tendency of this traffic descriptor again matches the intuition: with higher traffic demands the descriptor grows.

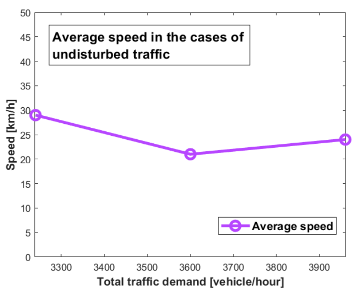


Figure 7
Average vehicle speeds for three different traffic demands served by undisturbed traffic

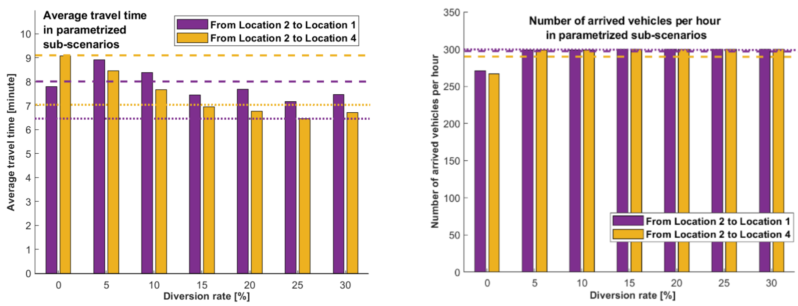
In Figure 7, the average vehicle speed within the target road subnetwork is shown. The diagram does not seem to follow a clear pattern, and does not match the intuition; with higher traffic demands, the average vehicle speed first decreases, then slightly increases.

3.2.2 The Second Base Scenario and its Parametrized Sub-Scenarios

The smooth road traffic is hindered by the unexpected appearance of an obstacle at the road location labelled with B#2 in Figure 2:

- The dotted lines in the subfigures of Figure 8 indicate ATTs and NAVs per hour, respectively, for the FS, i.e., for the undisturbed, smooth traffic.
- The traffic congestion formed because of the obstacle is then mitigated – in consecutive simulation experiments – by increasing γ from 0% to 30% by steps of 5%. The traffic situations that take shape in the SBS and the PSSs are characterized also by the aforementioned diagrams. These show how the ATTs and the NAVs per hour change – as proxy parameter γ increases – for routes hit hard by the obstacle, namely for Routes 2 → 1 and 2 → 4.
- The dashed lines indicate ATTs and NAVs per hour, respectively, for the second scenario with EDR based on recent traffic information.

The diagrams in the subfigures of Figure 8 are to be compared to the diagrams prepared for the first case study, i.e., to Figures 5a and 5b. The diagrams in Figures 5 and 8 have been prepared for the nominal D_{total} only, and shows the ATTs and NAVs per hours of particularly hard-hit routes.



(a) (b)

Figure 8

The traffic situations that take shape in the SBS and the PSSs of the second case study. Also, the effect of EDR – based on recent traffic information – is shown. The ATTs (a) and the NAVs per hour (b) for Routes 2→1 and 2→4 for the nominal total traffic demand.

To illustrate how – according to the PSSs of the second scenario within the second case study – ATTs along a particularly hard-hit route, namely along Route 2 → 1, change as γ, T_{stop}, $T_{decision}$, and D_{total} are varied in consecutive simulation experiments, three separate diagrams are included here as subfigures of Figure 9.

In the mentioned diagrams, proxy parameter T_{stop} was set to 30s, 60s, and 90s, respectively. The interpolated ATT-surfaces corresponding to the following γ values have been included therein: 0%, 10%, 20% and 30% (i.e., step of 10%).

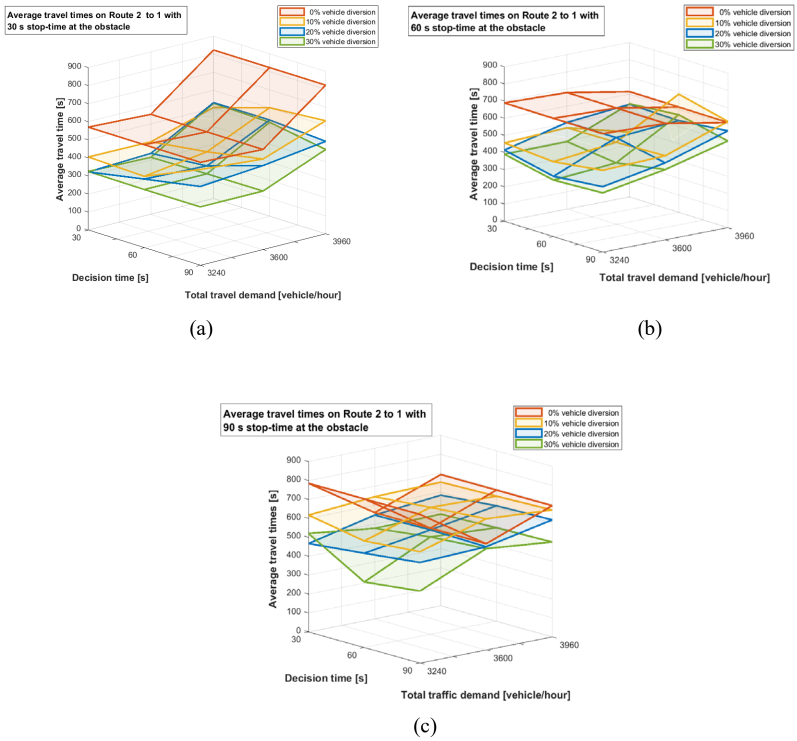


Figure 9

The ATTs on Route 2→1 – for various decision times, traffic demands, diversion ratios – in the traffic disturbed by the obstacle. The stop-times at the obstacle are 30s (a), 60s (b) and 90s (c), respectively.

3.3 Discussion of the Traffic Simulation Results

According to the microscopic traffic simulations carried out in conjunction with the first case study, the following traffic conditions and changes can be observed for the FS, the SBS, and the PSSs based on Figures 3, 4 and 5:

- Figure 3 shows calm, fairly light, undisturbed traffic that has formed according to the FS.
- In Figure 4a, on the other hand, the full-blown effect of the obstacle, which appeared in the target road network at a busy road location B#1, on the traffic can be perceived: a continuous vehicle queue has built up on a hard-hit road, and the traffic situation has worsened considerably. This situation can be gauged by considering that the ATT on the hardest hit route, i.e., Route 3→4 has grown about 9 times of its FS value, while the NAV per hour has reduced to about 25% of its FS value.

- In case of the PSSs corresponding to γ values of 5% and 10%, the ATTs and NAVs per hour, see Figure 5, have improved compared to the respective values computed for the SBS in respect to the Routes 2→4 and 3→4. A screenshot of the traffic according to the latter PSS is shown in Figure 4b. These improvements are due to the fact that some the drivers/ AVs started using low-capacity local roads to reach their destinations. These diversions have resulted in somewhat reduced road traffic near the obstacle location B#1, and have decreased the length of the queue that has originally formed there.
- For the PSSs corresponding to γ values of 15% and 20%, the ATTs on both considered routes started to increase, i.e., worsen, while the NAVs per hour continued to increase, i.e., improve, according to Figure 5. This is due to the higher number of vehicles using now the local roads; however, using local roads results in longer travel times, thereby increasing also the considered ATTs. On the other hand, the queue has become considerably shorter near the obstacle location B#1, as it can be verified in Figure 4c for the latter PSS.
- For the PSSs of 25% and 30% diversions, the ATTs, as well as the NAVs per hour considered have worsened according to Figure 5. The explanation for this is that even though the queue near the obstacle location has become considerably shorter than for the preceding PSSs, the local roads are now getting congested causing more delays and causing vehicles to be stuck there. A screenshot of traffic according to the latter PSS is shown in Figure 4d.
- In Figure 5, the ATTs and NAVs per hour computed for the different PSSs can be compared to those computed for the FS, and to those computed for the hindered case when recent traffic information was used by the drivers/AVs for EDR.

According to the microscopic traffic simulations carried out in conjunction with the second case study, the following traffic conditions and changes can be observed for the FS, the SBS, and the PSSs based on Figures 6-9:

- In Subsubsection 3.2.1, the FSs[6] of the second case study with different total travel demands were looked at. In this context, Figures 6 and 7 present diagrams of four specific traffic indicators – computed for the undisturbed traffic – versus D_{total}. The descriptors presented in this manner were the average delay, average delay due to stops, average number of stops and average vehicle speed. The first three of these four behaved as expected, the fourth, however, did not show a clear pattern.

[6] Note that the FSs are shared by the two case studies, as only the hindered cases are different for the two case studies.

- In Subsubsection 3.2.2, the traffic situations that take shape in the SBS and the PSSs of the second case study were looked at. In this context, Figures 8 present diagrams of ATTs and NAVs for two hard-hit routes at the nominal total traffic demand.
- Also, in Subsubsection 3.2.2, the SBS and PSSs of the second case study were looked while several parameters were varied as:
  - In the subfigures of Figure 9, the ATTs on a particularly hard-hit route have been presented for various values of T_{stop}. The ATTs behave in regards to this proxy parameter as expected, for longer stop-times the ATTs tend to grow.
  - In each subfigure of Figure 9, the interpolated ATT-surfaces –drawn in red, yellow, blue and green – tend to lower as γ increases from 0% to 30% by steps of 10%. The ATTs behave in regards to this proxy parameter more or less as expected.
  - In regards to D_{total}, the ATTs tend to grow, though this behavior of theirs is not that clear cut.
  - In regards to proxy parameter $T_{decision}$, the ATTs do not follow a clear pattern. $T_{decision}$ could be related to urban texture[7] near and around the obstacle and the queues.

The hindrances caused by the obstacles associated with the two case studies presented herein can be gauged by comparing Figures 5 and 8. Based on this comparison, one finds that the SBS according to the first case study caused considerably greater hindrance to the traffic than the SBS of the second case study. This comparison, as well as the analysis of further traffic descriptors that not have not been included herein, signifies a higher utility of the OTCD capability in the first case study than in the second.

4 Traffic Situations Not Relieved by Local Traffic Congestion Mitigation Approaches

In the previous section, two nonrecurrent traffic congestion cases were looked at in two separate case studies. The cases considered therein can be mitigated by local traffic congestion mitigation approaches, including also the OTCD based approach described in Subsection 1.2. On the other hand, according to Conjecture

[7] In a lightly built-in area, the LoS detection of the traffic congestion could be quicker and more reliable than in a densely built area. Therefore, when modelling the visibility from the nearby crossroads, the lightly built-in area could be associated with a shorter $T_{decision}$, while the densely built area with a longer $T_{decision}$,..

3 put forward in Subsection 1.1, there are traffic situations and transport tasks/assignments that do not lend themselves to local traffic mitigation approaches. An example[8] from Budapest, Hungary for such a situation is given below:

- The transport task is to get/drive to the Budapest Airport (BUD) from the city center in a short time by car in order to reach either an outgoing flight departing from BUD, or to meet a passenger arriving to the airport onboard an incoming flight.

Of course, one can choose the fast, but accident-prone, narrow expressway, along which one can – in undisturbed traffic – drive relatively fast, but in the peak hours, and in case of some even minor traffic incident on the road, the traffic comes to a stand-still for a while; or one can choose some slower route that has more alternatives, moreover, the route itself and all its alternative routes taken into consideration bypass the expressway toward the airport.

Based on the simulation experiments presented in Section 3, and on the above example from Budapest, one can realize the importance of available alternative routes both, in traffic congestion mitigation and in routing. Then, when analyzing and tackling these and similar adverse traffic situations, one could think in terms of groups of routes rather than in terms of individual routes[9]. For instance, sticking to Budapest, if someone wants to drive from a location on the Pest side, i.e., from the eastern half of the city, to a location on the Buda side, i.e., to the western half, they can choose between different Danube bridges to reach the intended destination. In this example, the bridges could well be used to identify the route groups.

In certain road networks, depending on the urban texture of and the traffic control and management arrangements implemented, a route can be slightly modified via taking a short local detour within its own route group when the driver/AV encounters a minor disturbance along their planned route. In this sense, there are route groups that are robust against minor traffic disturbances, and there are groups, which are not.

Based on the route group concept, a new, or at least uncommon, route optimization criterion can be specified. Furthermore, this approach can and should be combined with the LoS problem/task/approach used herein. Referring back to the second motto, with the above outlined routing approach, which considers the existence, and number of local route alternatives, the queues arising because of

8 Note that this example underlines also the relevance of the third motto. A further point to the mentioned motto: the handbook cited therein was published before the proliferation of intelligent, and/or connected vehicles, and AVs; since then, and due to the spread of such vehicles on roads, the number of essential road design parameters should be increased from the stated two to three. See further details in [30].

9 The notion of route is used now in its original sense, not as O-D pairs.

some unexpected minor incident at some neuralgic road location could be totally bypassed, and the transport assignment – or mission as referred to in the motto – need not be aborted at all. The outlined route optimization approach could find applications in military, police and security related route planning tasks, but could also in fairly common, everyday tasks.

It is not to say that the above outlined routing approach is always applicable in real-world situations. The mission mentioned in the second motto needs to be aborted during its execution (because of some traffic jams and blocked roads encountered). Relying on the above outlined routing approach, the aforementioned mission might not even start: it may become a mission impossible right at the beginning (due to some real-world time constraint, e.g., driving along the safer route featuring many local alternatives routes might take too long to reach the intended flight). The above outlined approach is simply too caution.

When – after further research, modelling, implementation and validation efforts – the approach outlined above reaches the maturity to deal with real-world applications, it will need to consider:

a) Actual traffic intensity
b) Multilane sections of the roads
c) Different vehicle priorities
d) Dealing with short critical sections of the route
e) Looking at the most critical traffic situations could also facilitate its application in real-world traffic situations and routing tasks.
f) The seriousness of the traffic incident
g) The traffic intensity dependent accident rates
h) Visibility degradation due to adverse weather conditions

Conclusions

In the frame of the study presented herein, traffic simulation experiments were carried out for a concrete urban road subnetwork, to explore the joint effect of road vehicles' individual traffic congestion avoidance efforts, in which, onboard visual LoS, ECSs and related OTCD capabilities were put to use. Two realistic case studies were carried out to investigate the effect of non-recurrent, unexpected traffic incidents. The presented Vissim-based simulation experiments concerned themselves with the comparison of undisturbed, disturbed and mitigated traffic.

In addition, the traffic effects of the hindrances described in the case studies were compared. The process of congestion detection, avoidance and mitigation was tentatively modelled via proxy parameters in the manuscript. In certain simulation experiments, several proxy parameters were varied and the corresponding results assessed.

In Section 4, a new objective was proposed for route planning and optimization in sensitive traffic situations and in case of sensitive transport assignments. Further research aspects were mentioned in the text.

Acknowledgements

This research was supported by the European Union within the framework of the National Laboratory for Autonomous Systems (grant: RRF-2.3.1-21-2022-00002). It was also supported by the NRDI Office, Budapest, Hungary (grant: 2018-2.1.10-TÉTMC-2018-00009).

References

[1] Payalan, Y. F.; Guvensan, M. A. Towards next-generation vehicles featuring vehicle intelligence. IEEE Trans. Intell. Transp. Syst. 2019, 21, 30-47

[2] Ortiz, F. M.; Sammarco, M; Costa L. M. M.; Detyniecki, M. Appli-cations and services using vehicular exteroceptive sensors: a survey. IEEE Trans. Intell. Veh., 2022, 1-20

[3] Marti, E.; de Miguel, M. A.; Garcia F.; Perez, J. A review of sensor technologies for perception in automated driving, IEEE Intell. Transp. Syst. Mag. 2019, 11(4), 94-108

[4] Feng, D.; Haase-Schütz, C.; Rosenbaum, L.; Hertlein, H.; Gläser, C.; Timm, F.; Wiesbeck, W.; Dietmayer, K. Deep multi-modal object detection and semantic segmentation for autonomous driving: datasets, methods, and challenges. IEEE Trans. Intell. Transp. Syst. 2021, 22(3), 1341-1360

[5] He, J.; Tang, Z.; Fu, X.; Leng, S.; Wu, F.; Huang, K.; Huang, J.; Zhang, J.; Zhang, Y.; Radford, A.; Li, L. Cooperative Connected Autonomous Vehicles (CAVs): Research, Applications and Challenges. In Proceedings of IEEE 27th International Conference on Network Protocols, Chicago, IL, USA, 2019

[6] Marron, A.; Limonad, L.; Pollack, S.; Harel, D. Expecting the Unexpected: Developing Autonomous System Design Principles for Reacting to Unpredicted Events and Conditions. In: Proceedings of IEEE/ACM 15th International Symposium on Software Engineering for Adaptive and Self-Managing Systems, pp. 167-173, 2020, Seoul, South Korea

[7] Wolhuter, K. Geometric Design of Roads Handbook. CRC Press, Boca Raton, FL, USA, 2015

[8] World Health Organization (WHO): European regional status report on road safety 2019, Available online: https://apps.who.int/iris/handle/10665/336584 (accessed on 18 Oct, 2022)

[9] Jayasooriya, S. A. C. S.; Bandara, Y. M. M. S. Measuring the Economic Costs of Traffic Congestion. In Proceedings of 2017 Moratuwa Engineering Research Conference, pp. 141-146, Moratuwa, Sri Lanka, 2017

[10] Fazekas, Z.; Obaid, M.; Boulmakoul, A.; Karim, L.; Gaspár, P. Utility assessment of line-of-sight traffic jam and queue detection in urban environments for intelligent road vehicles, in: Boulmakoul, A., Karim, L., Bhushan, B. (Eds.), Intelligent Distributed Computing for Trajectories. CRC Press, Taylor & Francis Group, Boca Raton, FL, USA, 2022, pp. 207-228

[11] Thandavarayan, G.; Sepulcre, M.; Gozalvez, J. Cooperative perception for connected and automated vehicles: evaluation and impact of congestion control. IEEE Access 2020, 8, 197665-683

[12] Lu, Q.; Tettamanti, T.; Hörcher, D.; Varga, I. The impact of autonomous vehicles on urban traffic network capacity: an experimental analysis by microscopic traffic simulation. Transp. Lett. 2020, 12, 540-549

[13] Bohra, S. Design Manual Adjustments and Infrastructure Needs for Automated Vehicles: City of Toronto context. MSc thesis, Ryerson University, Toronto, Ontario, Canada, 2019

[14] PTV VISSIM. Available online: https://www.ptvgroup.com/en/solutions/products/ptv-vissim/ (accessed on 22 Dec, 2022)

[15] PTV Planung Transport Verkehr AG., VISSIM 4.10 User Manual, 2005, Karlsruhe, Germany

[16] Parisot, C.; Meessen, J.; Carincotte, C.; Desurmont, X. Real-time Road Traffic Classification Using On-board Bus Video Camera. In: Proceedings of 11th International IEEE Conference on Intelligent Transportation Systems, pp. 189-196, Beijing, China, 2008

[17] Chakraborty, P.; Adu-Gyamfi, Y. O.; Poddar, S.; Ahsani, V.; Sharma, A.; Sarkar, S. Traffic congestion detection from camera images using deep convolution neural networks. Transp. Res. Rec. 2018, 2672 (45), 222-231

[18] Akhtar, M.; Moridpour, S. A review of traffic congestion prediction using artificial intelligence. J. Adv. Transp. 2021, article-id. 8878011

[19] Zanella, A.; Bazzi, A.; Pasolini, G.; Masini, B.M. On the impact of routing strategies on the interference of ad hoc wireless networks. IEEE Trans Commun 2013, 61(10), 4322-4333

[20] Bazzi, A.; Berthet, A. O.; Campolo, C.; Masini, B. M.; Molinaro, A.; Zanella A. On the design of sidelink for cellular V2X: a literature review and outlook for future. IEEE Access 2021, 8, 97953-97980

[21] Hu, L.; Ou, J.; Huang, J.; Chen, Y.; Cao, D. A review of research on traffic conflicts based on intelligent vehicles. IEEE Access, 2020, 8, 24471-483

[22] Ullah, M. R.; Khattak, K. S.; Khan, Z. H.; Khan, M. A.; Minallah, N.; Khan, A. N. Vehicular traffic simulation software: A systematic comparative analysis. Pakistan J. Eng. Appl. Sci. 2021, 4(1), 66-78

[23] Ramadhan, S. A.; Joelianto, E.; Sutarto, H. Y. Simulation of traffic control using Vissim-COM interface. Internetworking Indones. J. 2019, 11 (1), 55-61

[24] Bansal, P. Matlab-Vissim interface for online optimization of green time splits. arXiv preprint: arXiv:2007.15208, 2020

[25] Valentine, D. T.; Hahn, B. Essential MATLAB for Engineers and Scientists. Academic Press, London, United Kingdom, 2022

[26] Chen, M. Modeling and Simulation Analysis of Road Network Based on VISSIM. In: 2019 International Conference on Intelligent Transportation, Big Data and Smart City, Changsha, China, 2019, pp. 32-35. IEEE

[27] Farhan, M.; Martin, P. T. Evaluation of the benefits of route guidance system using combined traffic assignment and control framework. In: Proceedings of 17th ITS World Congress, ITS Japan, ITS America, Busan, South Korea, 2010

[28] Savrasovs, M.; Pticina, I.; Zemlyanikin, V. Wide-Scale Transport Network Microscopic Simulation Using Dynamic Assignment Approach. In: Proceedings of the International Conference on Reliability and Statistics in Transportation and Communication, Riga, Latvia, 2017, pp. 241-251

[29] Permana, A. Y.; Susanti, I.; Dewi, N. I. K.; Wijaya, K. Morphology of urban space: model of configuration using logic of space theory in densely populated of Bandung City. Journal of Architectural Research and Education 2019, 1(1), 18-35

[30] Fazekas, Z.; Balázs, G.; Gyulai, C.; Potyondi, P.; Gáspár, P. Road-type detection based on traffic sign and lane data. J. Adv. Transp. 2022, 6766455