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Choosing Routes in Urban Areas that are Robust Against Minor Nonrecurring Traffic Incidents

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Abstract
The paper looks at certain vehicle-level re-routing issues within urban road networks, and related network-level traffic management issues. These arise mostly when the traffic along a route of significance is hindered, slowed down, or even blocked because of some – possibly minor – unexpected, nonrecurring traffic incident at a sensitive road location, or road section. Considerations for planning routes in urban areas – routes that are in some sense robust against such incidents – are presented herein. Also, the on–the–spot detection of traffic queues by an ego-vehicle – relying on data streams from on-board visual line-of-sight (LoS) exteroceptive sensors watching, scanning and monitoring the ego-vehicle's road environment, and by some on-board dedicated real-time detection systems processing and analyzing the incoming data streams – is touched upon. However, this traffic congestion avoidance and mitigating approach – effectuated either by individual autonomous vehicles, or by human drivers – presumes availability of alternative routes, which is not the case for a good portion of the route considered. A route planning approach that could be used for routes with such critical sections is proposed and motivated through an example of an urban route of significance.

Keywords
urban road traffic management, traffic congestion mitigation, microscopic traffic simulation, route planning

1 Introduction

Aggregated traffic data from cities around the world, e.g., such data collected and published by Beedham (2022), indicate that road traffic in urban road networks is hectic from time to time. Particularly, the peak hours are problematic in the cities reviewed by the report, but presumably also in many other cities around the world. Herein, the task of choosing routes within urban areas that are in some sense robust against minor nonrecurring traffic incidents is addressed. Such a task is exemplified and motivated through the example of a traffic congestion that forms – due to some minor traffic incident – along a concrete traffic sensitive urban route. The congested traffic and the traffic congestion mitigation measures are modelled and examined herein via a series of parametrized microscopic traffic simulation experiments; the results of these are then discussed and conclusions are drawn. Accordingly, the rest of the paper is organized as follows. In Section 2, the route planning task mentioned above is motivated and brought to the focus from a somewhat wider range of urban road traffic related topics addressed in the literature. In Section 3, the example of a traffic sensitive urban route, namely of one leading from the city center to the airport in Budapest, Hungary, is considered. Also, in this section, the importance of choosing routes that are in some sense robust against minor nonrecurring traffic incidents is pointed out. Then, such a route planning approach is presented and explained with reference to microscopic traffic simulation experiments carried out for the aforementioned traffic sensitive route. In Section 4, conclusions are drawn, as well as directions of further research are put forward. From these directions, the integration of the proposed route planning approach into a more general route planning/optimization (RPO) framework should be accentuated here.

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2 Related literature

The problems caused by hectic urban traffic mentioned in the Introduction, and by the traffic congestion arising due to such traffic, manifest themselves at and affect different levels of urban life and interaction, as well as the economy, argues Gössling (2016). The author opines that these problems and particularly their economic and social costs are generally not shared by the various layers/groups of urban society in a fair manner. For instance, health issues caused by hectic traffic directly touch upon the lives of car drivers, while the hectic traffic also affects other road users, including pedestrians and cyclists, and local urban residents in general.

The above health issues are put in a wider context by Giles-Corti et al. (2016), who emphasize the role of proper city planning in mitigating the adverse effects associated with hectic traffic and traffic congestion. According to Memon et al. (2020), driving/travelling in traffic congestion within megacities can be a tiring and nerve-racking experience for car drivers and passengers alike. This conjecture has been confirmed by a wealth of studies that assess the maleficent effects of lacking transport infrastructure, and of the resulting traffic congestion, as well as of the increased travel time-delays on mental health and wellbeing of drivers, other traffic participants and urban residents. Sixty-nine such studies – published between 2000 and 2021 – are cited, classified and assessed by Conceição et al. (2023) in their review paper.

Beside health issues, many other problems of different nature that are caused by, or can be linked directly to hectic urban traffic and traffic congestion could be mentioned. These problems range from the high numbers of road accidents, a problem analyzed by Cabrera-Arnau et al. (2020), through the problems of increased air and noise pollution in cities, phenomena addressed by Zaky and Soubra (2021), to the deterioration of social interactions, and the worsening of livability and amenity of modern cities, social phenomena looked at by Rui and Othengrafen (2023). Despite of having been identified lately as a 'major challenge with a substantial impact on safety, economy, and even climate' by Falek et al. (2022), route planning and optimization (RPO) has become over the last few decades an essential service for road users worldwide. Initially, it was used mostly by car drivers; more recently, however, its 'userbase' has grown to include autonomous vehicles (AVs), as well. A number of popular RPO services and applications are assessed and compared by Siuhi and Mwakalonge (2016), while the importance of RPO services and applications in achieving fluent urban road traffic within contemporary cities is pointed out and demonstrated by Paiva et al. (2021). In their paper, Zhang et al. (2022) propose a multi-objective optimization-based approach to RPO. Their proposed optimization framework considers travel time, distance, cost and personal preferences, and employs an improved depth-first search algorithm to find the optimal route. The evaluation of their framework on real-world traffic data indicates its feasibility and the applicability.

Analyzing car drivers' driving behavior and route choices, Jabbarpour et al. (2018) showed that car drivers tend to rely on RPO services in urban road networks to prevent long delays in their travel/transport schedule, to optimize fuel-consumption of their own vehicles, and to minimize their own psychological distress. For human car drivers, RPO service is particularly important when they drive in areas and/or along routes that they do not frequent regularly. Furthermore, as urban road networks can be rather complex, it is far from being obvious to navigate and get around in them quickly and efficiently without up-to-date geographic and road network information at hand. This difficulty is felt distinctly by elderly drivers, and by drivers with only brief driving experience. These aspects of driving, navigation and road network awareness are analyzed by Vrkljan and Polgar (2007), and more recently by Yang et al. (2021).

Beside necessary geographic and road network data, RPO services/methods, as well as urban traffic management systems (TMSs), may make use of historical traffic data. For instance, Castro et al. (2012) rely on such data in their urban traffic modelling and prediction computations. Nonetheless, according to Wan et al. (2019) and Chavhan and Venkataram (2020), the real benefit for car drivers/AVs comes with dynamic rerouting options implemented within the RPO services/methods; these options, however, require real-time, possibly crowdsourced traffic data. On the other hand, in their above cited paper Falek et al. (2022), seeking answers to questions like when, how often, and where rerouting is worthwhile in major urban road networks, find that – if accurate historical traffic data is relied upon in RPO at departure time – rerouting a vehicle surprisingly seldom turns out to be really beneficial. Their analysis was based upon road traffic data from three mega-cities, namely from New York, London, and Chicago. The respective data had been collected over several months for these cities. The authors conclude that dynamic rerouting typically should only be employed during rush hours, for long routes that pass through some very specific road segments. Clearly, location and traffic awareness is essential also in case of AVs, as shown by Sarker et al. (2020), and it is nearly indispensable in freight transport, as demonstrated by Xidias (2019). The latter statement is corroborated by Tsekeris (2022), who reports that a good portion of global freight transport is realized in urban road networks. According to Pan et al. (2012), the detection and prediction of traffic congestion are important, but non-trivial traffic management tasks. Nowadays these tasks are accomplished by urban TMSs. Such systems are reviewed by Ravish and Swamy (2021); several of these systems incorporate and provide RPO services for drivers/AVs.

The TMS presented by Pan and his colleagues collects real-time position and speed data from 'floating' vehicles, and collects traffic flow data from road-side sensors to support detection and prediction of traffic congestion. It computes proactive, individually-tailored rerouting guidance, which is pushed to vehicles when signs of traffic congestion are observed on their route. Three rerouting strategies are taken by the authors, namely the multipath load balancing strategy, which considers expected future vehicle positions, the random multipath load balancing, and the dynamic shortest path strategies. All these strategies significantly decrease the average travel (ATT) compared to a no-rerouting baseline method.

Other TMSs, such as the one described in Filho et al. (2020), rely on inter-vehicle communication and artificial intelligence methods for estimating the traffic congestion level in order to maximize the traffic flow. The authors make use of an ensemble of classifiers to estimate actual traffic congestion levels. This traffic information is then disseminated to the vehicles concerned. The 5G based Internet of Vehicles (IoV) is a relatively new branch of communication technology, which is – according to Benalia, et al. (2020) – expected to alleviate various traffic problems associated with major cities. The application of 5G based IoV for urban traffic management, and in particular, for traffic congestion alleviation, is surveyed by Kalsoom and Khalid (2018). They list and evaluate different TMSs, as well as a number of related technologies. The authors observe that TMSs lessen traffic accident rates and reduce pollution. Furthermore, they analyze the roles of the various architectural layers – within TMSs – in increasing traffic efficiency. Afrin and Yodo (2020) review quantitative road traffic measures published in the literature. The authors implement a number of these and compute their actual values for several historical urban traffic datasets. The authors point out and compare the advantages and disadvantages of these measures. They opine that a subset of these measures can be used to gauge the sustainability and the resilience of urban road networks and the road traffic formed therein, as well as to characterize the different traffic congestion states. They acknowledge that there are various reasons, which can cause traffic congestion. Depending on these reasons, congestion can be classified into recurring and nonrecurring. The former occurs regularly, mostly due to the excessive number of vehicles in the traffic, e.g., during peak hours.

On the other hand, unpredictable events, such as bad weather, urgent/unreported work zones, traffic incidents and mass/public events, are common causes of the latter. Quite common events, such as a vehicle running out of fuel, or breaking down on its way, also belong to nonrecurring traffic incidents. Some of the causes listed above are related neither to the actual traffic, nor to peak-hours, however, the severity of the impedimental effect, i.e., of the traffic congestion caused is very much related to these factors. In respect of the prevalence of the congestion subtypes, the authors refer to the statistical data collected and published by Cambridge Systematics, Inc. (2005). According to this report, nonrecurring road traffic congestion contributes to more than half of all traffic congestion – at least – within the USA.

Gorji et al. (2022) evaluate and propose to improve urban transportation networks' resilience in short-term non-recurring traffic congestion based on graph connectivity measures. As a concrete example, they look at the resilience of the Isfahan (Iran) road network, and identify critical nodes and arcs within it. Clearly, such a graph-based approach is applicable also in other urban areas of the world. Fazekas et al. (2022) propose to alleviate nonrecurring, initially unreported road traffic congestion through evasion of blocked road sections by individual road vehicles that either approach these road locations, or are already close to these. The authors consider both human-driven vehicles and AVs participating in the traffic, and carry out microscopic traffic simulation experiments – in respect of a particular urban road network – to explore the aggregated effect of the individual traffic congestion avoidance efforts. In case of AVs, on-board visual line-of-sight (LoS) exteroceptive sensors and on-board traffic jam and queue detection (TJQD) capabilities are assumed and put to use. This approach requires visual LoS constellation between the ego-vehicle and some of the vehicles in the queues ahead. Clearly, this constellation changes dynamically with the traffic.

In their paper, the authors approximate the visual LoS TJQD process and the avoidance of the queues in a much simplified way using proxy parameters; they, however, anticipate that the road traffic – involving vehicles with the aforementioned capabilities – could be more accurately modelled via a static, fine-grain graph-based representation of the road network. Presumably, the above representation would be more detailed and finer-grain than, say, the one proposed and used by Gorji et al. cited above (2022).

3 A traffic sensitive route leading from the city center to the airport in Budapest, Hungary

Although several approaches have been considered in Section 2 for mitigating nonrecurring urban road traffic congestion, none of these approaches can prevent the traffic congestion forming – under conditions of normal day-time traffic – in case of a possibly minor traffic incident that takes place somewhere along the traffic sensitive urban route mentioned in the section title. From these approaches, the RPO approach proposed by Fazekas et al. (2022) is applied herein. The traffic congestion that forms along the aforementioned route is analyzed in Section 3.1. It should be noted that the on-board visual LoS TJQD capabilities looked at in the above cited paper – capabilities expediently building upon and augmenting more common capabilities provided by advanced driver assistance systems (ADAS) and autonomous driving (AD) systems – turned out to be useful in route guidance and traffic congestion mitigation for the cases considered therein. It is true, even if alternative route guidance solutions, such as crowd-sourcing of traffic incidents and anomalies, or making use of smart road infrastructure supported by leading edge communication solutions could produce similar, or even better results after an initial delay. The utility of on-board visual LoS TJQD capabilities in the mentioned cases was established – through series of microscopic traffic simulation experiments – both in respect of the individual vehicles, and other participants of urban road traffic. In the cases looked at in the cited paper, vehicles with TJQD capabilities had enough time, and also had the option to act upon the queue-warnings in a timely manner and evade the congested road sections. In the example looked at herein, however, the visual LoS detection of the forming queues happens too late, so it does not help in evading the traffic congestion that has – in fact – already set in. The reasons for the mentioned delay in queue detection could be varied, these include e.g., undulating topography, and/or buildings/structures restricting, or even blocking the view from and also blocking any 'escape route' for the ego-vehicle equipped with TJQD capabilities.

3.1 A specific scenario

As a concrete RPO example, which is a specific scenario for the considered route rather than the route on its own, the task of driving/travelling on road from central Budapest to the Budapest Liszt Ferenc International Airport (BUD) – in a short time – is considered herein. The main point for the driver and/or the passengers, which is specifically emphasized here, is not to miss a given flight leaving from, or arriving to the airport. Clearly, one can choose to drive/travel along the fast, but accident- and traffic incident-prone, narrow, obsolete expressway, which has only one traffic lane in each travel direction, and features physical barriers on both sides, and which – according to general consensus amongst car drivers regularly using this road – should have been replaced by, re-built, or upgraded to a motorway decades ago. A route from central Budapest to BUD, which is also the route of an airport bus service, operated by the Centre for Budapest Transport, that includes the obsolete expressway mentioned above as a section, is drawn in light blue on the Google Earth image shown in Fig. 1. The roads drawn in yellow are major roads within the city's road network. The satellite image shows the central and south-eastern districts of the capital city. In the sequel, the aforementioned route will be referred to as Route 1. A brief description of this route and those of two other routes are given in Table 1. By using Route 1, one can – in case of undisturbed traffic – drive/travel quite fast and get to the airport quickly, and reach the intended flight comfortably. In peak hours, however, particularly in case of some – even minor – traffic incident occurring somewhere along the expressway, the traffic there slows down considerably, or even comes to a standstill, and consequently the intended flights could well be missed by drivers/passengers travelling along Route 1 and heading for BUD. Alternatively, one can choose a slower, less direct route – with a 50 km/h speed-limit all along – that features a number of alternatives throughout the way to BUD; furthermore, this route and all its alternative routes bypass the mentioned obsolete expressway. With such a route choice, assuming that only minor incidents could occur along this route and the alternative routes, the airport/flight can be reached on time for sure, provided the departure to the airport takes place at the pre-planned time, i.e., at a departure time that can be planned – sufficiently

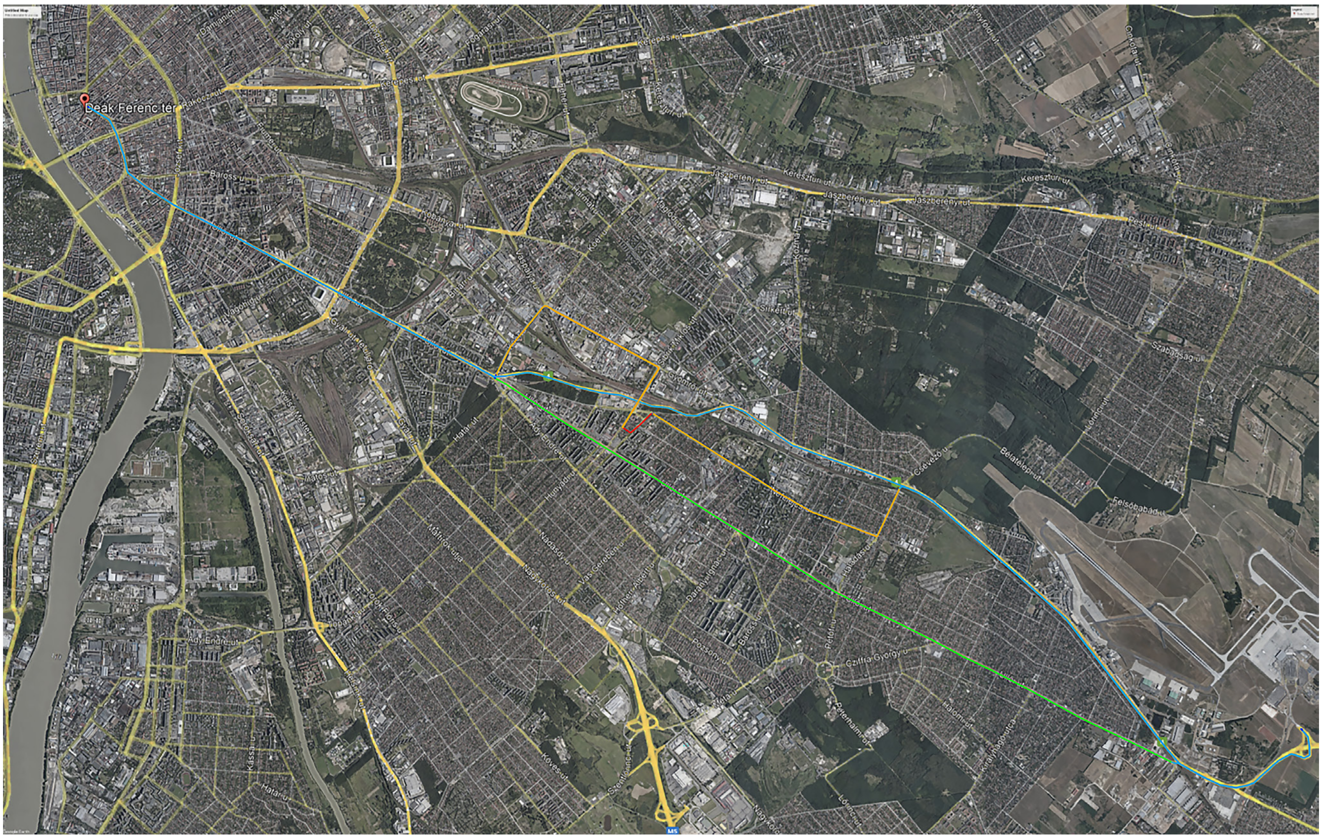

Fig. 1 Three routes leading from the city center to BUD: Route 1, which includes an obsolete expressway section is drawn in light blue, Route 2 is drawn in green, and Route 3 in orange on the Google Earth image

Table 1 Brief description of the three routes shown in Fig. 1

Route	Length	Description
Route 1	20.25 km	Includes a 5.56 km long obsolete express-way section with physical barriers on the sides The above road section includes a 2 km low-speed section for modelling a traffic incident
Route 2	19.57 km	Has alternatives with only short local detours
Route 3	22.84 km	Has alternatives with only short local detours

accurately – in advance. The essence of this routing approach is to consider groups of routes rather than individual routes. Accordingly, the robustness – the term used in the title of this paper – refers to these groups of routes rather than to individual routes. Herein, it is assumed that groups of routes differ in only short local detours from each other.

3.2 Traffic simulation experiments in respect of the considered traffic sensitive route

Microscopic traffic simulation experiments were implemented in Vissim (PTV Planung Transport Verkehr AG., 2022) and were carried out to demonstrate the vulnerability of the urban road traffic along Route 1 in case of some possibly minor traffic incident. The above vulnerability is critical in the specific scenario described in the previous subsection. The vulnerability of the traffic shows up clearly in the simulation results presented in Tables 2 and 3; especially, the values appearing in the rightmost column,

Table 2 The traffic congestion formed due to a nonrecurring traffic incident along the considered sensitive route is characterized by three descriptors computed for a one-hour simulation period

Scenario	Average speed	Average number of stops	Number of arrived vehicles
Route 1 without delay	39.8 km/h	76.2	1000
Route 1 with delay	21.7 km/h	168.1	506

Table 3 The traffic congestion formed is characterized by the same descriptors as in Table 2, but these values were computed for a two-hour simulation period

Scenario	Average speed	Average number of stops	Number of arrived vehicles
Route 1 without delay	39.8 km/h	76.2	1000
Route 1 with delay	23.7 km/h	201.7	1000

i.e., the numbers of arrived vehicles, are telling. The congestion formed along Route 1 is characterized in the tables by three selected traffic descriptors computed for 1000 vehicles taking this route. To produce the simulation results presented in Table 2, the traffic simulation modelled a one-hour time-period, whilst for those given in Table 3, a two-hour period was used. Within the one-hour period, the vehicles departed from central Budapest to BUD in the first 45 minutes, and in the remaining 15 minutes there were no further departures. In case of the two-hour modelling period, the vehicles departed in the first 45 minutes, while during the remaining 75 minutes there were no further departures, and the target road network was allowed to empty out. In this way, vehicles stuck in the congestion – in case of the simulation experiments summarized in Table 2 – could finally complete their tardy journeys, as indicated by the number of arrived vehicles in Table 3. Further to the above experiments, the minor traffic incident itself – together with its direct effect on the traffic – was modelled in the experiments via setting up a designated 2 km long low-speed road section within expressway. In Tables 2 and 3, the presence of this low-speed section is referred to simply as 'delay' (in the leftmost column).

3.3 Parametrized traffic simulation experiments involving also alternative routes

Apart from Route 1, two further routes, namely Routes 2 and 3, were considered in the parametrized traffic simulation experiments (PTSEs). All these routes are shown in Fig. 1, and are described briefly in Table 1. Routes 2 and 3 feature the local alternatives discussed in Subsection 3.1. Though

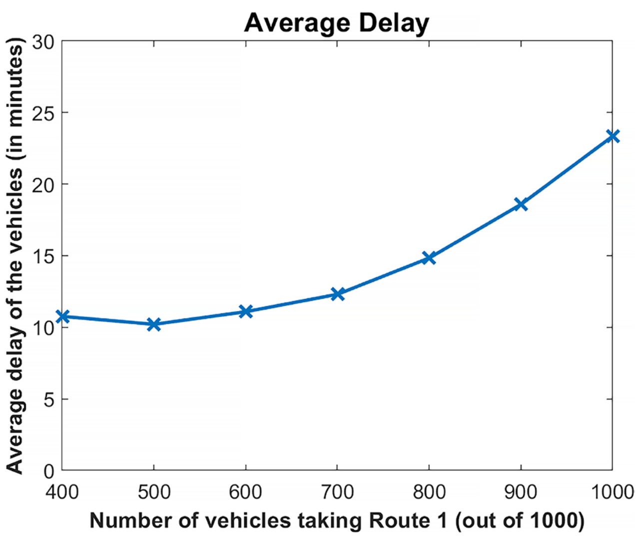

Fig. 2 Average delay – experienced by a vehicle – computed for a series of parametrized experiments

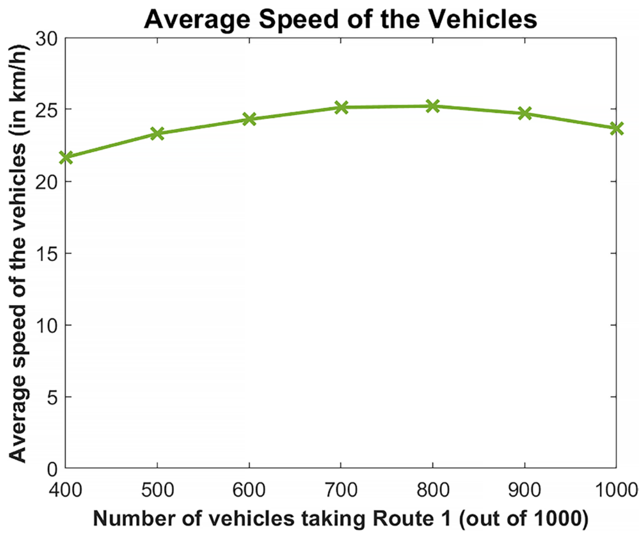

Fig. 3 Average vehicle speed in the presented series of parametrized experiments

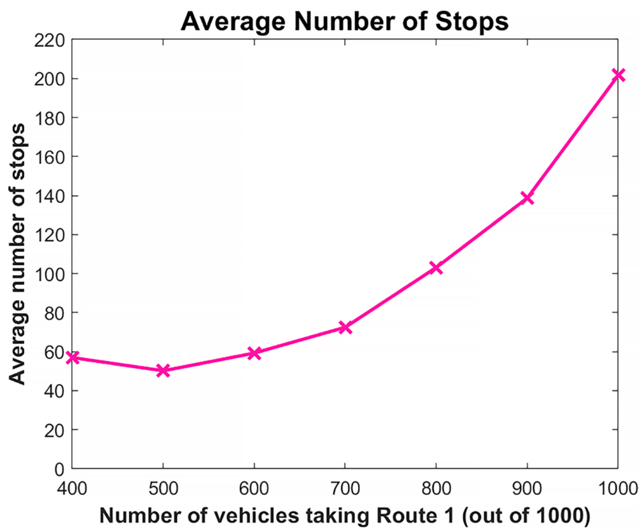

Fig. 4 Average number of stops – experienced by a vehicle – in the presented series of parametrized experiments

driving along Route 2 and 3 takes more time – in case of fluent traffic – than driving along Route 1, the former two routes are robust against minor traffic incidents, e.g., occurring in day-time traffic, whilst Route 1 is not robust at all. For this reason, in the specific scenario described in Subsection 3.1, Route 2, or Route 3 should be chosen instead of the traffic sensitive Route 1. It should be noted that RPO that takes into account the availability and the number of alternative nearby routes, or in other words, considers groups of routes, rather than individual routes, could find applications also in military, police and security related route planning tasks. In the rest of this subsection, the conventional traffic congestion mitigation potential of Routes 2 and 3 – in respect of Route 1 – is looked at via a series of PTSEs. In these PTSEs, two-hour periods were modelled in the manner detailed in the previous subsection, however, in these experiments, only a portion of the vehicles took Route 1, the rest of the vehicles – in equal numbers – took Routes 2 and 3 instead. The number of vehicles taking Route 1 is used herein as the parameter for the PTSEs. In Figs. 2–4, three traffic descriptors, namely average delay, average speed of the arrived vehicles, and average number of stops – gained from the PTSEs – are presented diagrammatically. Figs. 2–4 indicate that Routes 2 and 3 are also viable routes to BUD. More interestingly, Figs. 2–4 indicate that such a diversion of road traffic is useful in mitigating the traffic congestion once it has been reported to the traffic management center and has been broadcast to the car drivers and AVs, but not before. Consequently, the aforementioned specific scenario cannot be properly handled through this conventional traffic congestion mitigation approach.

4 Conclusions and further work

The task of choosing routes in urban areas that are robust against minor nonrecurring traffic incidents has been addressed in the paper. The task has been exemplified and motivated through a nonrecurring traffic congestion that forms along a neuralgic urban route in Budapest due to such an incident. The congested traffic and its mitigation has been modelled via microscopic traffic simulation experiments and the results of these have been discussed. Also, the importance of the availability of local alternative routes has been pointed out. As part of future work, the requirement of and preference for urban routes that are robust against minor nonrecurring traffic incidents need to be incorporated into a more general, multi-faceted route optimization framework; one such framework was mentioned in Section 2. As cited therein, Zhang et al. (2022) proposed a multi-objective optimization based approach to RPO. Their approach could well handle and seamlessly incorporate the driver preferences that have been looked at and emphasized in the present paper. In case of certain road trips/tasks/missions, the availability of alternative routes is imperative. In other relevant cases, the availability of route alternatives that feature only minor/local differences can be critical, or can be of high importance. First, the requirement of and preference for such route alternatives, respectively, need to be algorithmically implemented and coded. Second, the implemented route planning routine could then be incorporated into the cited multi-objective optimization procedure and validated. In order to do so, experimentation with and assessment of measures quantifying the number of local route alternatives will be necessary. Also, appropriate relative weights need to be worked out that make allowance for the more common driver preferences, but also bring out aspects emphasized herein.

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