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Mitigating urban motorway congestion and emissions via active traffic management

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ABSTRACT

Due to unavoidable expansion of car-ownership, traffic congestion and emissions in developing countries keep on increasing. Meanwhile, high construction costs and statutory restrictions hinder traditional road infrastructure expansion and improvement projects. Thus, exploring cost-effective traffic management solutions to relieve traffic congestion and emissions becomes one of the most significant challenges faced by transportation authorities, especially in developing countries. Active traffic management (ATM) systems that are environmentally sustainable and relatively low-cost are particularly advantageous. In this study, we develop an integrated ATM system to mitigate urban motorway congestion and emissions. The proposed system can be used directly with existing road facilities, which provides a cost-effective way for traffic management and decarbonization in developing countries. The simulation results show that the developed system can reduce travel time spent (TTS), carbon dioxide (CO_2) and nitrogen oxides (NO_2) by 7.5%, 21.1% and 10.7%, respectively.

1. Introduction

Due to unavoidable expansion of car-ownership, traffic congestion and emissions in developing countries keep on increasing. In order to solve the problem, we can intervene via infrastructures (e.g. additional lanes, geometric design improvement, etc.) or via traffic management systems. However, high construction costs, statutory restrictions, constrained right-of-way and environmental factors hinder traditional road infrastructure expansion and improvement projects. Exploring cost-effective traffic management solutions to relieve traffic congestion and emissions becomes one of the most significant challenges faced by transportation authorities, especially in developing countries. Active traffic management (ATM) systems that are environmentally sustainable and relatively low-cost are particularly advantageous, as they exploit the utilization of existing motorway infrastructures.

The commonly used motorway ATM strategies are variable speed limit (VSL), ramp metering (RM), high occupancy vehicle (HOV) lanes, reversible lanes (RL), automated highway systems (AHS) and hard shoulder running (HSR) (Guerrieri & Mauro, 2016; Li & Ranjitkar, 2015; Li, Ranjitkar, & Ceder, 2014; Li, Ranjitkar, & Zhao, 2016). HSR is one of the most promising ATM measures, which uses the motorway shoulder as a general-purpose lane. Most HSR systems are used at a fixed time of day during weekdays, aiming at mitigating recurrent traffic congestion during peak hours. HSR can be also implemented in urban contexts to support smart cities (Wang, David, Chalon, & Yin, 2016), for traffic incident management (Ma, Hu, Hale, & Bared, 2016), and as priced dynamic shoulder lanes (PDSLs) (Brewer, 2012). The success of HSR has been evidenced by various empirical studies performed in European and North American countries (Fuhs & Brinckerhoff, 2010; Geistefeldt, 2012; Guerrieri & Mauro, 2016). The majority of these studies performed statistical comparison of before-after analysis on the magnitude of safety and operational benefits or losses due to HSR using historic data (Bhouri, Aron, & Scemama, 2016; Haj-Salem, Farhi, & Lebacque, 2014; Kononov, Hersey, Reeves, & Allery, 2012).

One concern about the use of HSR in developing countries is the lack of necessary facilities. HSR is certainly not a general solution for all the developing counties from low to middle-income ones. However, HSR is applicable in certain countries with basic traffic management systems. The World Bank examined three major developing regions (i.e., East Asia, Eastern Europe, and Latin America) and found that all three regions have implemented basic systems for traffic management (Yokota, 2004). These systems include facilities required by the implementation of HSR, such as closed-circuit television (CCTV) and variable message signs (VMS). The introduction of HSR can benefit traffic management in

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these developing countries via maximum utilization of their existing facilities.

In our previous attempts, we have developed a series of ATM systems for congestion management (Li, Ranjitkar, & Zhao, 2019; Li & Wagner, 2020; Li, Zhao, & Cao, 2020). This research explores the potential benefits of combining ATM with a truck-only policy. The proposed ATM system integrates HSR and VSL, and aims to mitigate motorway congestion and emissions. The proposed system can be used directly with existing road facilities, which provides a cost-effective way for traffic management and decarbonization in developing countries.

2. Related work

Active traffic management has been applied in various countries. In Germany, HSR is implemented with speed harmonization to handle recurrent congestion and bottlenecks, but can be also used for non-recurrent congestion or incidents. The first HSR system was installed in the late 1990s, and nowadays it is applied on around 250-km of motorway network with a 100 km/h speed limit (Geistefeldt, 2012). In the Netherlands, the principle of HSR has been established since 2003, with motorways including the A15, A27, A28 and A50 using peak-hour lanes. Today, HSR is used on approximately 1000-km of motorway network. In the UK, the Managed Motorways programme began in 2006 with a pilot scheme on 11 miles along the M42 Motorway. The hard shoulder is used as a traffic lane at peak hours coupled with VSL. Considering the safety issue, additional emergency refuge pull-outs are spaced every 1600 ft (0.31 miles) with emergency call boxes (Sultan, Meekums, Ogawa, Self, & Unwin, 2009). In Italy, HSR is applied on the A14 (23.6-km-long) and on "the Mestre bypass motorway". In France, a static HSR has been operated on a weaving section of motorway A3-A86 where a likely negative impact on safety due to higher speed was reported, while a dynamic HSR has been applied on motorway A4-A86 only during peak hours, with no negative impact on safety. In North America, there are a number of HSR implementations (Fuhs & Brinckerhoff, 2010): on motorways SR-826 and SR-836 in Florida since 2005, on motorway I-805/SR-52 in California since 2005 (HSR is activated when traffic speed is below 30 mph), on motorway GA-400 in Georgia since 2005 (HSR is activated when traffic speed is below 35 mph), on motorway US-29 in Maryland with a maximum 55 mph speed limit, and finally in New Jersey, Virginia and Washington.

2.1. Operational benefits

With the widespread use of HSR in motorway traffic management, various studies have been conducted to assess its operational benefits. After implementing HSR, the motorways in the Netherlands witnessed a 7% to 22% overall capacity increase, 1 to 3-min trip time reduction, and up to 7% traffic volume increase during congested periods (Taale, 2006). Geistefeldt (Geistefeldt, 2012) analyzed the effect of HSR on traffic flow characteristics and motorway capacity based on loop detector data from a 18-km stretch of motorway A5 between Friedberg and Interchange Frankfurt Northwest in Germany. Analysis results revealed that the capacity of a three-lane carriageway was increased by 25% with the use of HSR during peak hours. The total duration of congestion per year on these sections could be reduced by up to 90%. Significantly high acceptance of HSR among truck drivers was observed. In Switzerland, an exploratory analysis was conducted using data from radar sensors installed along a two-lane motorway stretch between Geneva and Lausanne (A1) (Samoili, Efthymiou, Antoniou, & Dumont, 2013). The authors concluded that the implementation of HSR resulted in a 10.6% capacity increase and maintenance of speed at 100 km/h. Haj-Salem (Haj-Salem et al., 2014) assessed the implementation of the RM and HSR simultaneously on the Ile de France motorway network that consists of 24 controlled on-ramps. The reported results indicated that the integrated control can dramatically improve the traffic condition on the test area. Bhouri et al. (Bhouri et al., 2016) described a HSR experience on a France motorway weaving section which is shared by a two-lane urban motorway ring (A86) round Paris and a three-lane west-east urban motorway (A4). They observed an indirect impact of HSR on the daily traffic distribution. More specifically, a shift of traffic demand from daylight off-peak hours (HSR closed) to peak hours (HSR open) was observed. Daylight traffic decreased by 5% at off-peak hours and increased by 2% at peak hours. Meanwhile, they reported a positive impact of HSR on travel time reliability.

2.2. Safety issues

Although the operational benefits of HSR have been proven by the aforementioned studies, it is still necessary to discuss potential issues concerning safety when HSR is deployed. In the Netherlands, the number of accidents causing injury on the motorways with HSR decreased by 13% from the before period (2004–2005) to the after period (2006–2007) (In't Veld, 2009). Aron et al. (Aron, Cohen, & Seidowsky, 2010; Aron, Seidowsky, & Cohen, 2013) reported that the main effect of HSR on a France motorway section (A4-A86) is the reduction in traffic density, and therefore in the number of accidents. This is to be expected since congested traffic is often associated with a higher risk of accidents than free-flow traffic. However, this positive effect can be partially counterbalanced by the migration of density and of accidents downstream due to HSR. Kononov et al. (Kononov et al., 2012) investigated the relationship of flow, density, and speed to the crash rate on selected motorways in Colorado. They suggested that HSR is a possible strategy to deal with the deficit of available deceleration distance associated with a mix of high speeds and short headways. The authors also suggested that the safety gains of HSR are likely to outweigh its losses which can be further moderated by constructing pullouts, increasing courtesy patrols, and using VSL and real-time queue warnings. Geistefeldt (Geistefeldt, 2012) observed a slight increase in the number of accidents on the motorway sections with HSR. Nevertheless, this effect is often compensated by a decrease in the accident frequency on the upstream sections, which might be because of the lower risk of rear-end collisions due to the reduced extent of congestion. Guerrieri Mauro (Guerrieri & Mauro, 2016) forecasted the HSR implementation on a 128-km stretch of the Italian motorway A22. They stated that the utilization of HSR can lead to a considerable capacity increase (up to 35%) with slight variations in the general safety conditions.

2.3. Summary

Existing studies have researched a well-established consensus that the utilization of HSR has a positive effect on motorway operations. The motorways equipped with HSR recorded considerable increase in capacity and reduction in travel times. In terms of safety, there exist certain discrepancies in the body of literature. For example, In't Veld (In't Veld, 2009) reported a significant reduction in the number of accidents causing injury after applying HSR, whereas Geistefeldt (Geistefeldt, 2012) observed a slight increase in the accident frequency on the motorway sections with HSR. Nevertheless, there is no clear evidence showing that the implementation of HSR causes any dramatic deterioration in safety. It should be noted that previous field-based studies paid little attention to user environmental performance of HSR and limited optimization-based HSR strategies have been proposed.

3. Truck-only Hard Shoulder Running (T-HSR)

In this section, the proposed Truck-Only Hard Shoulder Running (T-HSR) Strategy is presented. First, we illustrate the control logic of the strategy. Following this, a T-HSR configuration is demonstrated in the context of UK motorway systems.

3.1. Control logic

In this study, a rule-based T-HSR strategy is proposed, which is easy-to-use and straightforward to road operators. Fig. 1 shows a flowchart of the proposed T-HSR control strategy which is applied to each T-HSR controlled section. For each control interval, the information from loop detectors and CCTV cameras is collected. The collected volume data is averaged and converted to the Passenger Car Unit (PCU). The proportion of trucks is calculated based on the converted volume. Then, the computed variables are compared with a set of pre-determined thresholds. When the converted volume V is greater than the threshold V_{hdr} and the proportion of trucks P_{trk} is greater than the pre-determined threshold P_{hdr}, the information from CCTV cameras (100% coverage of the hard shoulder) is used to identify obstructions. Once the hard shoulder is confirmed to be free of obstructions, HSR is activated in reverse flow order to ensure that no vehicle will encounter an obstacle after entering the motorway. In this study, we set the control interval length as 15-min for HSR and 5-min for VSL, as fluctuating too often can increase driver confusion and stress. VSL is applied for all the lanes. For PCU conversion, passenger car = 1.0, Light Goods Vehicle (LGV) =1.0, and Heavy Goods Vehicle (HGV) = 2.3 are used, which are recommended by Transport for London (TfL) (Smith, Blewitt, et al., 2010).

Experiences from existing HSR systems (Chase & Avineri, 2008; Geistefeldt, 2012; Samoili et al., 2013) show that opening the hard shoulder as a running lane causes increased speeds on neighboring lanes due to the sudden reduction in traffic density. They recommend the use of a speed harmonization system (e.g., VSL) whenever HSR is in effect. Thus, we integrate the T-HSR with the existing VSL control strategy for the M25 motorway in the UK (Rees, Harbord, Dixon, & Abou-Rahme, 2005), as shown in Fig. 1. When T-HSR is activated, the maximum speed limit is set as L_{hdr}. The M25 VSL strategy computes appropriate speed limits based on detected vehicle volumes: the speed limit changes from 70 mph (national speed limit) to 60 mph when volume exceeds 1650 veh per hour per lane (veh/h/ln); it is further lowered to 50 mph when volumes exceed 2050 veh/h/ln. The minima of L_{hdr}, 60 mph, and 50 mph are chosen as the final speed limits to be displayed on the Variable Message Signs (VMSs).

3.2. T-HSR Configuration

Since this research aims to provide a cost-effective solution for motorway traffic management, the T-HSR strategy is designed to be directly applicable to existing motorway systems. Fig. 2 shows the available ATM facilities in the UK. In the T-HSR implementation, Incident Detection and Automatic Signaling (MIDAS), operated by induction loops in the motorway, are adapted to obtain counts of different types of vehicles (e.g., passenger car and trucks) which are essential for calculating control inputs – the traffic volume and truck proportion. A network of fixed CCTV cameras, positioned to cover 100% coverage of the hard shoulder, are employed to ensure that the hard shoulder is clear from obstructions. VMSs are placed every 800 m to provide road users with adequate guidance of the speed limits and lane availability:

- Under free-flow conditions, VMSs on running lanes are blank. The hard shoulder is reserved for emergency use only, with a “Red X" lane closure signal.
- When the traffic demand increases, as detected by the MIDAS induction loops, VMSs on running lanes display a lowered speed limit. The hard shoulder remains closed, with a “Red X" signal.
- When T-HSR is activated, the hard shoulder is opened through posting a speed limit on VMSs for all running lanes and the hard shoulder, and a message showing “Hard Shoulder Open for Trucks Only” on the driver information signal.

4. Evaluation methodology

4.1. Test bed selection

In this study, a 12-mile (19.3-km) stretch of motorway M25 (also known as the London orbital motorway) in the UK with 5 junctions was selected as the test bed (see Fig. 3). High traffic demands from Heathrow airport, M3, M4, A308, and M25 itself makes it one of the most congested stretches of road in Europe. Statistics from the UK department for Transport[1] show that the section consistently records the highest daily traffic counts on the British strategic road network, with an average flow of 219,492 vehicle/day. Thus, this stretch provides an ideal test bed to verify the proposed T-HSR strategy under heavily congested conditions. There are 5 lanes from J15 to 12 and 4 lanes from J12 to J11. HSR is implemented on all the sections within the study area for HSR except for the sections with acceleration and deceleration lanes. The maximum volume observed at the downstream of J12 is 2148 pch/h/ln.

4.2. Simulation model

Traffic simulation is a cost-efficient tool to assess the performance of different motorway control measures before implementing them in the field. We simulated the selected motorway stretch using the AIMSUN micro-simulator (AIMSUN, 2020). The data used in this study was obtained from Highways England.[2] The dataset provides the number of vehicles less than 5.2 m, between 5.21 and 6.6 m, 6.61–11.6 m, and above 11.6 m, as well as the average speed of all vehicles within the 15-min time slice. We collected the data for 2019 from 42 detectors that are installed on the mainstream, entry slip roads, and exit slip roads of the selected stretch. The preliminary analysis results showed that the highest traffic demands were observed in June. Therefore, 6:30–9:30 AM on June 3, 2019, a typical weekday peak period, was chosen as the simulation period based on these preliminary analysis results.

We selected the lane-changing model developed by Erdmann (Erdmann, 2015). The model explicitly discriminates between four different motivations for lane-changing: 1) strategic change, 2) cooperative change, 3) tactical change and 4) regulatory change. We set the willingness for cooperative changing (0–1) and the eagerness for performing strategic lane changing (0-infinite) as 1 and 1 respectively.

The simulation model was calibrated against the data collected on June 3, 2019 and then validated against the data on June 17, 2019. GEH index (Dowling, Skabardonis, Halkias, McHale, & Zammit, 2004) was adapted for calibration as well as validation based on volume data. The GEH (Geoffrey E. Havers) index can be expressed as follows:

$$\mathrm{GEH} = \sqrt{\frac{\left(V_{simu} - V_{real}\right)^2}{\left(V_{simu} + V_{real}\right)/2}} \quad (1)$$

where V_{simu} is the simulated count using the AIMSUN model and V_{real} is the field count. A model is considered to be acceptable if the GEH values for more than 85% of the observed detectors remain below 5 (Wunderlich, Vasudevan, Wang, et al., 2019). In our case, 38 (90%) and 36 (86%) detectors among all 42 detectors produced GEH values that are smaller than 5 for calibration and validation respectively. Therefore, the model is accepted for further analysis.

4.3. Control setup

An Application Programming Interface (API) program was developed to realize the T-HSR strategy in AIMSUN. During each control time interval, the T-HSR API receives traffic information from the detectors.

[1] https://web.archive.org/web/20191001163113/https://data.gov.uk/dataset/208c0e7b-353f-4e2d-8b7a-1a7118467acc/gb-road-traffic-counts

[2] http://tris.highwaysengland.co.uk/detail/monthlysummarydata

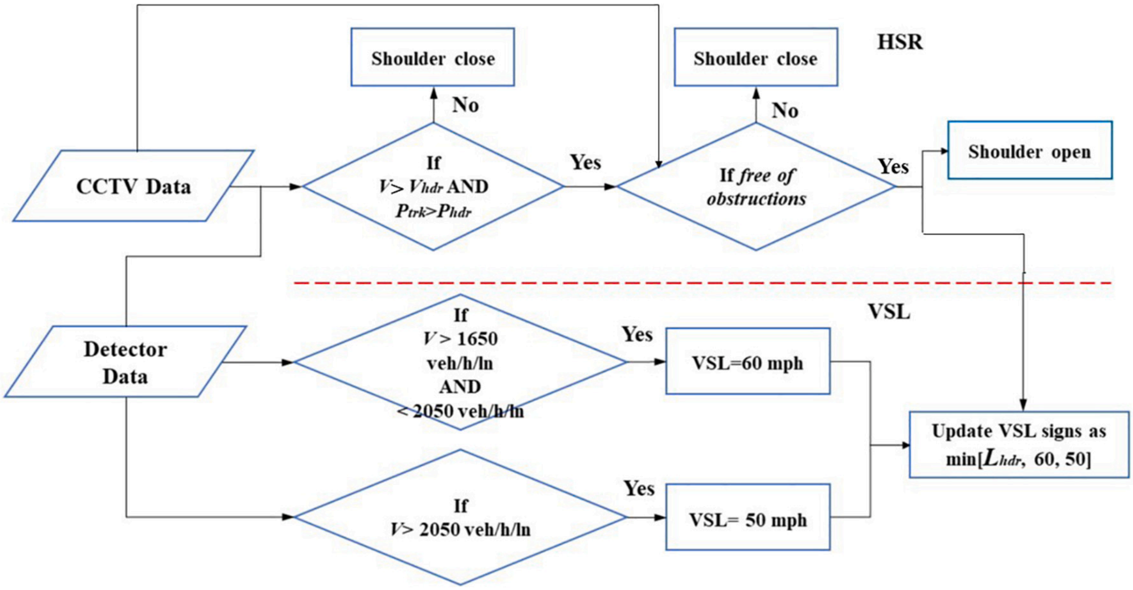

Fig. 1. Flowchart of T-HSR control.

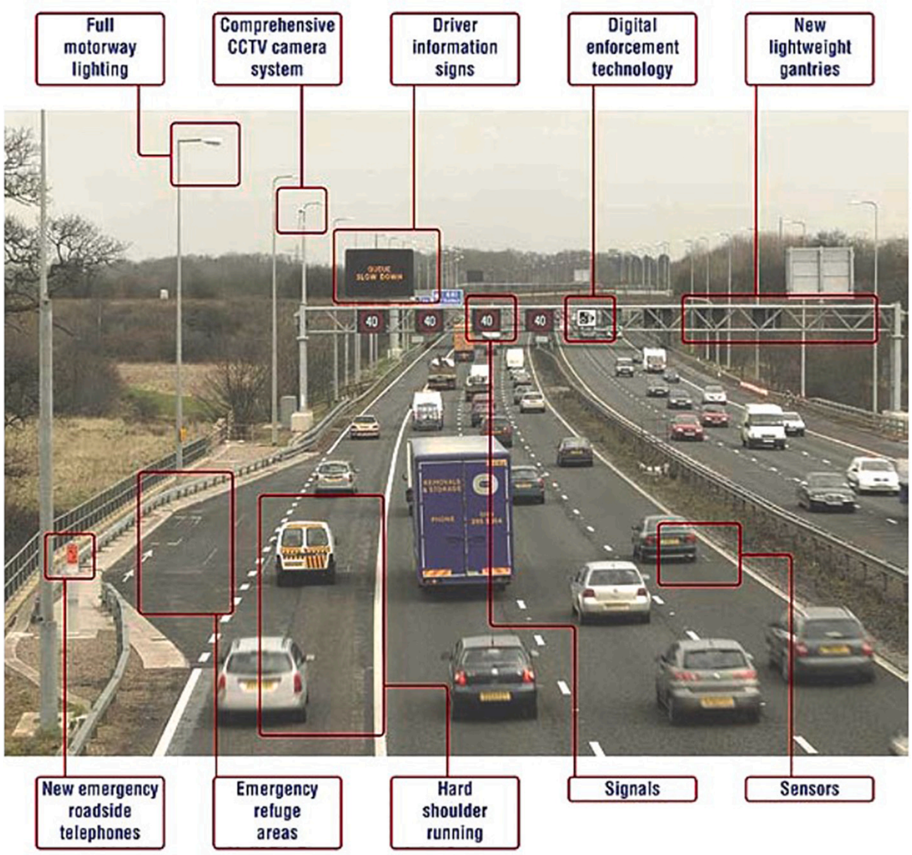

Fig. 2. Active Traffic Management facilities in the UK, source: the UK Highways Agency (UK Highways Agency, n.d.).

Then, the API determines control actions based on the designed control logic and real-time traffic information. Finally, the API exerts the determined VSL and HSR control actions by opening/closing additional lanes and adjusting the speed limits of the controlled sections, respectively. We tested a number of different combinations of threshold values in AIMSUN. More particularly, $P_{hdr} \in$ [10%, 12.5%, 15%], $V_{hdr} \in$ [1850, 1950, 2050 veh/h/ln], $L_{hdr} \in$ [50, 60 mph] were tested. We found that TTS increased with the increase of P_{hdr} as well as V_{hdr} values. $L_{hdr} = 50$ mph led to a higher total time spent (TTS) than $L_{hdr} = 60$ mph. The combination that yielded the lowest TTS was selected, these are $L_{hdr} = 60$ mph, $V_{hdr} = 1850$ veh/h/ln, and $PP_{hdr} = 10\%$.

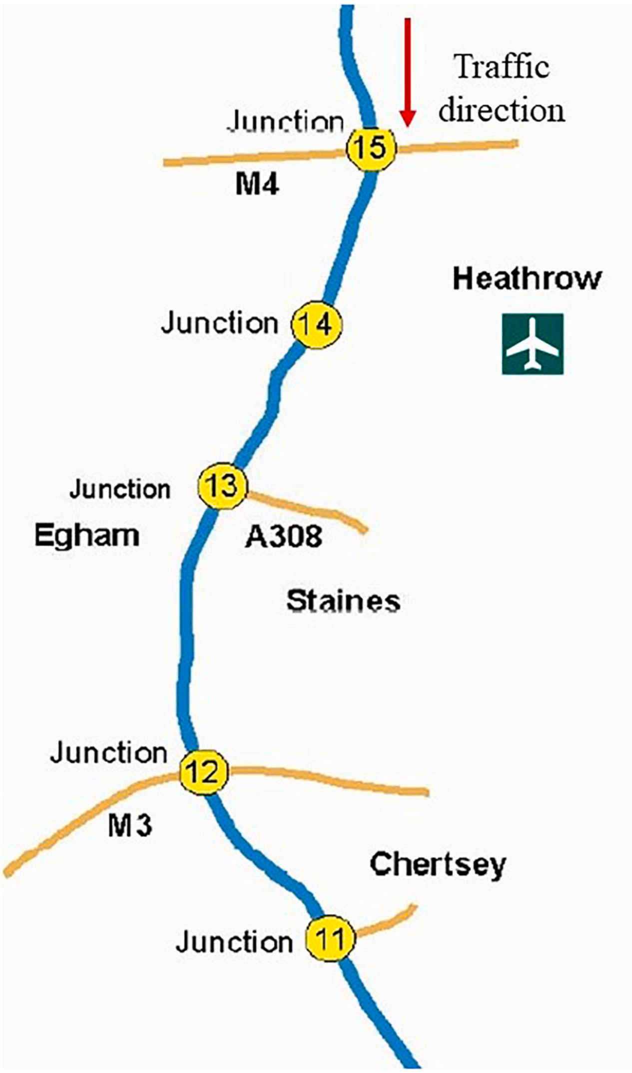

Fig. 3. Test bed: Junctions 15–11.

4.4. Performance effectiveness

We run the developed simulation model with 10 different random seeds. The results shown in this section are from a selected representative run. In this study, TTS was selected to reflect overall performance of the network. A lower TTS indicates lower delay, higher outflow, and therefore better traffic conditions. In this study, TTS was also used to optimize the threshold set of the proposed strategy.

The London Emission Model (LEM) (AIMSUN, 2020) embedded in AIMSUN was adapted to assess the environmental impact of HSR on the selected stretch. The LEM developed by Transport for London (TfL) is matched to London driving conditions (central, inner and outer London) and is underpinned by Real-Driving Emissions (RDE) data. Its average-speed emission functions can measure Carbon dioxide (CO2) and nitrogen oxides (NOx) emissions from configurable fleets of European vehicles. Thus, LEM is particularly suitable for our case – the London orbital motorway. In addition, the impact of HSR on driver behaviors was analyzed using two indicators, namely, the number of stops per vehicle and the total number of lane-changes.

5. Simulation results

In AIMSUN, we systematically tested three different control scenarios for the test bed, namely, no-control, all vehicle HSR (A-HSR), and T-HSR scenarios. The no-control scenario is chosen as a reference to measure improvements achieved by other control scenarios. In the A-HSR scenario, the hard shoulder is opened for all types of vehicles, and lane availability is determined by the control logic described in the section 3.1 without considering the truck proportion. In the T-HSR scenario, the proposed truck-only HSR strategy is used to manage motorway traffic flow. The results are presented under three sub-headings: mobility, emissions, and driver behaviors.

5.1. Mobility

Fig. 4 presents TTS computed for the entire study area of the motorway network under different control scenarios. The HSR for all types of vehicles yielded the lowest TTS (6708 h) among all the tested scenarios, which resulted in a 10.5% improvement compared with the no-control scenario (7493 h). The TTS computed using the proposed T-HSR strategy is equal to 6931 h, which is a 7.5% improvement compared against the no-control scenario. It can be observed that improvements contributed by HSR strategies were mainly during the peak periods, in this case from around 6:50 to 9:00 AM, indicating that HSR can effectively deal with high traffic demand. In addition, large variations in TTS measurements were observed for the no-control scenario, which might be caused by unstable traffic flow due to congestion. These variations were significantly reduced for both HSR scenarios. The less fluctuating travel time distribution can benefit drivers by providing them with more reliable journey time information.

Fig. 5 compares mainstream speed contours under different control scenarios. Note that HSR was activated mainly from 7 am to 9 am in the vicinity of J12 and J13. The color scale represents the level of traffic speed at the corresponding time and location. For the no-control scenario, an initial formation of congestion near the Junction 12 was observed, and then the congestion propagated to the upstream motorway sections. The congestion mainly resulted from a physical bottleneck at Junction 12. The red and yellow spots (representing slow moving traffic) have reduced significantly for the A-HSR and T-HSR scenarios when compared with the no-control scenario, representing significant improvement in the speed environment. It was also observed that the congestion migrated to the immediate downstream merging area at Junction 12 after implementing HSR. This is because extra traffic induced by the additional lane increased merging difficulties and traffic flow disturbances at the merging area. The simulation results also showed 8.9% and 11.2% increases in maximum volumes for A-HSR and T-HSR cases when compared with no-control case.

To further analyze the impact of different control settings on the proposed strategy, we tested 4 additional scenarios, as shown in Table 1. No-control scenario was used as a baseline to compute TTS changes due

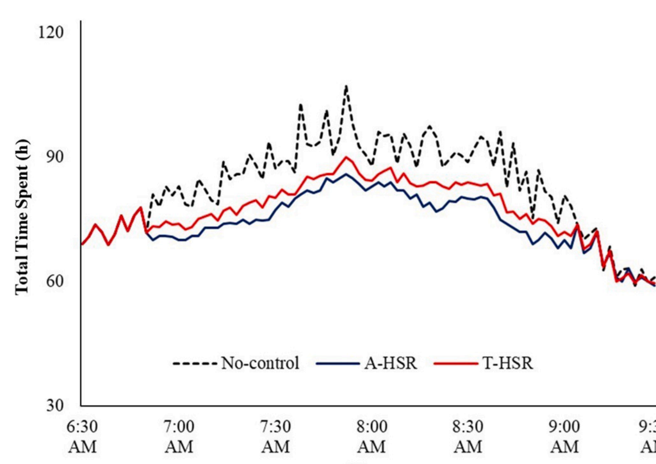

Fig. 4. TTS values under different control scenarios.

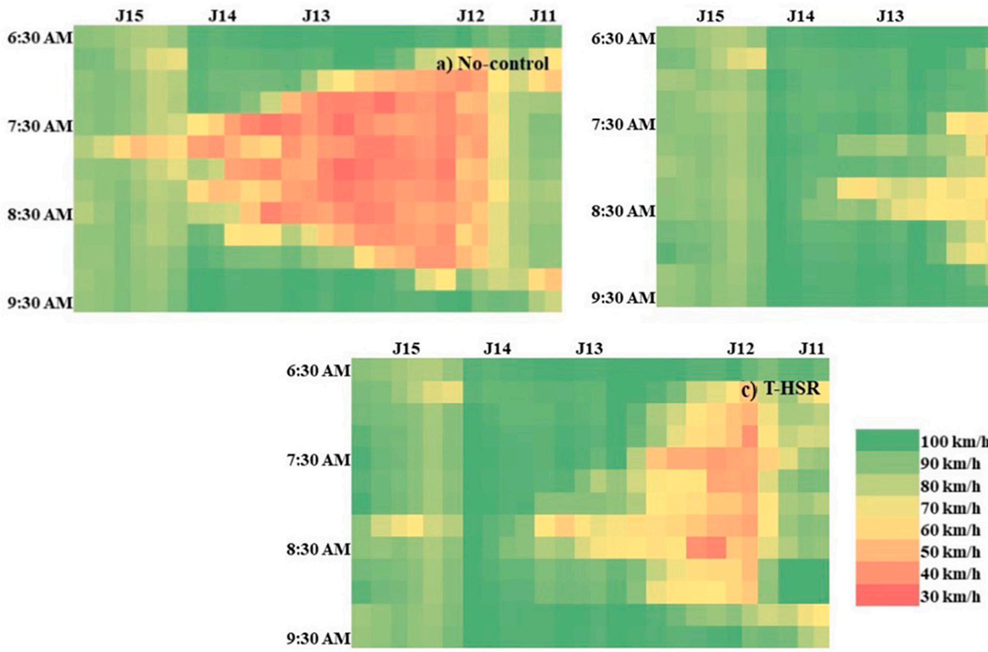

Fig. 5. Mainstream speed contours (travel from J15 to J11) under different control scenarios.

Table 1
TTS values for additional control scenarios.

Scenario	TTS(h)	change
No-control	7493	0%
T-HSR	6931	−7.5%
VSL	7298	−2.6%
T-HSR (no truck proportion threshold)	6841	−8.7%
T-HSR (6:30–9:30 am)	6534	−12.8%
T-HSR (7:30–8:30 am)	7126	−4.9%

to the tested scenarios. It was observed that solely implementing VSL resulted in limited improvement in TTS, which was less than 3%. T-HSR without considering truck proportion threshold recorded a higher improvement in TTS when compared with the original T-HSR case. We also tested two fixed-time T-HSR strategies in which the hard shoulder opened for trucks on all of the controlled sections during the pre-determined time. The simulation results showed that activating T-HSR for the whole simulation period (6:30–9:30) led to the lowest TTS among all the tested cases. T-HSR that was activated during 7:30–8:30 am witnessed around 5% improvement in TTS.

5.2. Emissions

Emissions computed using LEM for the entire test bed during the simulation period are shown in Table 2 where the unit is gram. For the A-HSR scenario, significant reductions occurred in the CO2 and NOx emissions, which were decreased by 25.0% and 23.2% respectively compared with the no-control scenario. The proposed truck-only HSR strategy achieved 21.1% and 18.7% reductions for the CO2 and NOx emissions respectively, when compared to the no-control scenario. In general, the environmental gains due to the T-HSR strategy are slightly lower than, but still comparable to, its counterpart (the HSR for all types of vehicles). In order to further investigate the reasons behind emission reductions due to HSR implementation, we analyze the impact of HSR on driver behaviors in the following subsection.

Table 2
Emissions under different control scenarios.

	No-Control	A-HSR		T-HSR	
	value	value	change	value	change
NO_x *(kg)*	2.84×10^2	2.18×10^2	23.2%	2.31×10^2	18.7%
CO_2 *(kg)*	1.05×10^5	7.88×10^4	25.0%	8.28×10^4	21.1%

5.3. Driver behaviors

Fig. 6a shows the total number of stops that occurred during the simulation under the three tested scenarios. It can be clearly observed that both HSR strategies produced more than 50% reduction in the total number of stops when compared to the no-control scenario. This can be explained by the fact that operating HSR relieved congestion, and therefore provided drivers with better traffic conditions. Furthermore, driving behaviors, such as abrupt acceleration and deceleration, and stop-and-go, are highly associated with vehicle emissions. Thus, during the HSR operation period, emission reductions were mainly attributed to the decreased number of stops and smoothed traffic flow (less abrupt acceleration and deceleration). We then analyzed the impact of HSR on lane-changing behavior, as shown in Fig. 6b. When the hard shoulder was opened, there were slight increases in the number of lane-changes. However, these increases were not that significant for the A-HSR (4%) and T-HSR (6%) cases when compared with the no-control scenario. The interaction between the mainstream traffic flow and outflow to the off-ramps was the main contributor to the increases in lane-changing behaviors.

6. Concluding remarks

This paper presents an integrated ATM system that uses HSR and VSL to mitigate motorway congestion and emissions. In particular, the developed system 1) determines HSR actions based on the real-time traffic volume and the truck proportion data, 2) is integrated with VSL and CCTV cameras to ensure safety, and 3) can be used directly with existing motorway facilities. The proposed strategy is systematically assessed for a 12-mile stretch of motorway M25 in the UK using micro-simulation. The following conclusions can be drawn based on the simulation results presented in the previous section:

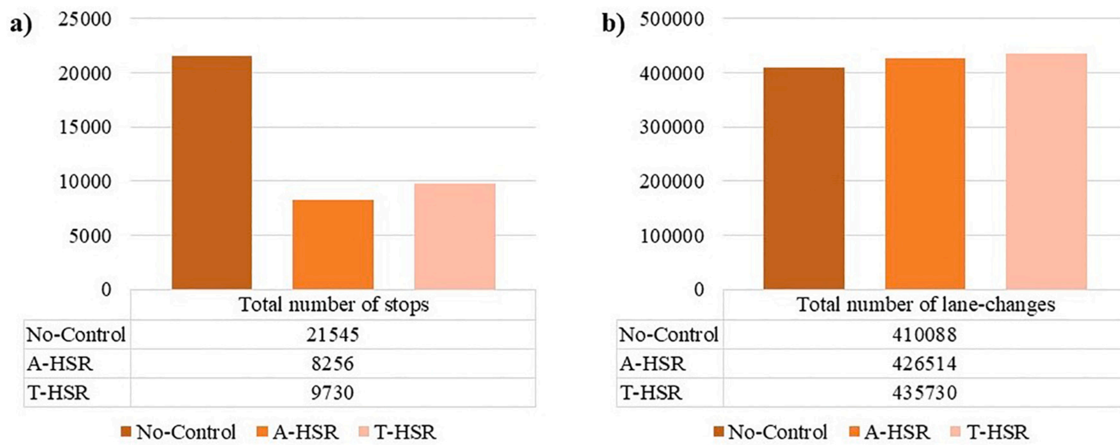

Fig. 6. Driver behaviors under different control scenarios.

- The developed ATM system can reduce the number of vehicle stops, which consequently results in a significant emission reduction;
- The operational and environmental gains due to the T-HSR strategy were slightly lower than, but still comparable to, its counterpart (the HSR for all types of vehicles).
- HSR induced a slight increase in lane-changing behaviors, which might be because of the interaction between go-straight and exiting traffic flows.

Although the simulation results show that the original HSR slightly outperformed the T-HSR in terms of mobility and environmental performance, the main advantage of the proposed T-HSR is improving user acceptance, which is difficult to evaluate using simulation tools. Deployment of HSR gives the hard shoulder an ambiguous character, leading to confusing situations for road users. For example, a commuter who is accustomed to an open hard shoulder during peak hours, may also expect it to be open during off-peak hours; road users may struggle to understand the complex signs and signals; or drivers who are unaware of HSR will not change to a new lane. These experiences inevitably decrease the user acceptance of HSR. The T-HSR is designed to improve user acceptance for two reasons. The first reason is that the willingness of truck drivers to use the motorway shoulder is higher than car drivers (Geistefeldt, 2012). The second reason is that trucks often travel on the leftmost lane (in the UK case), thus fewer conflict points are caused by HSR when only trucks are allowed to use the hard shoulder. In order to verify acceptance gains of T-HSR, a theoretical framework following existing technology acceptance theories will be established in future research. Then, a questionnaire-based survey will be conducted to quantify the level of user acceptance to the T-HSR strategy.

Author statement

Duo Li: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Software; Visualization; Roles/Writing - original draft.

Joan Lasenby: Conceptualization; Funding acquisition; Project administration; Resources; Supervision; Validation; Writing- Reviewing and Editing,

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