Investigation of driving behaviour transition during evacuation and its implication for traffic flow operations based on an open-source traffic simulation platform

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Abstract—Earlier studies have shown how driving behaviour during emergency evacuation is different from that under "normal" conditions. At the same time, most evacuation studies (where the driving performance is explicitly accounted for) were conducted under the assumption of a fully activated emergency environment. However, the transition phase in evacuation, from normal driving situations to emergency driving situations, and also its implication for traffic management has not yet been widely studied. During this phase, drivers receive evacuation information and instructions at different levels, which may induce heterogeneous behavioural driving response. The action and interaction of heterogeneous drivers would influence traffic flow operations. This paper is the pioneer to investigate this transition phase at the early stage of emergency situations and its implications for traffic flow operations. This is tested via a simulation study using a recently-developed open-source traffic simulation platform, where the driver behaviour (activation level, transition period) can be specified. Various scenarios are modelled showing the effect of time-varying (heterogeneous) individual driving behaviour based on a set of performance indicators at both network and individual levels (network clearance time, arrival rate, travel time). The analyses show that high penetration of activated drivers with a high activation level and a short transition period can significantly improve network performance. Therefore, traffic control and management can influence driving behaviour of evacuees towards such an optimal operation regime to improve evacuation efficiency.

Keywords—Evacuation; Transition phase; Driving behaviour; Activation level; Open-source traffic simulation

Introduction

Over the past decades, research on evacuation has attracted more and more attention. To set up an efficient and effective evacuation plan is essential. The control of the evacuation process is highly dependent on behaviour of evacuees, including both pre-trip evacuation choice and on-trip routing and driving [1, 2]. Evacuees' driving behaviour is considered as one of the most important influencing factors on evacuation performance [3, 4]. Since driving behaviour affects traffic flow, in particular road capacity, hence it is relevant to investigate in evacuation studies. More importantly, the behaviour of drivers under mentally demanding and emergencies is shown to differ from the normal situations (both from empirical observations and driving simulator studies [5, 6]).

Most of previous studies on evacuation driving performance assume a fully activated emergency environment (in contrast to "normal" conditions). However, the transition between normal traffic statuses and emergency situations (e.g., evacuation following a disaster), which typical appears at the beginning of an evacuation, has been overlooked. During this phase, drivers receive evacuation information and instructions at different levels, which may induce heterogeneous behavioural driving response. There may exist both normal and adapted drivers in traffic networks. It is not yet clear in what way the action and interaction of heterogeneous drivers may affect traffic flow operations. Here, the transition phase refers to the transformation of the traffic system from normal traffic conditions to evacuation conditions. The main focus of this paper is to analyse (quantify) the impact of this transition phase, considering the duration of the transition phase and the activation level of individual drivers, as well as to investigate its implications for traffic flow and traffic management.

A large amount of evacuation studies have been performed in both macroscopic and microscopic environments, such as DynusT, DYNASMART, EVAQ, Paramics, Corsim and Vissim/Visum (see overview in [1, 2]), This study is formulated at a microscopic level, and it allows to model individual driving behaviour. The main advantages in favour of microscopic traffic modelling are: (a) a comprehensive representation on the (behavioural) actions and interactions of individual travellers (instead of aggregate performance); (b) providing more detailed and reliable simulation results. In most of the commercial simulation packages, such as VISSIM, Paramics, the route choice and microscopic driving behaviour models are usually served as black boxes, which leave users limited degrees of freedom. Particularly in these black-box models, it is impossible to unravel which underlying mathematical and numerical choices have been made, and what the consequences of these are in terms of model validity. Therefore, in this study, the simulation is performed using a recently-developed open-source microscopic simulation platform (OTSim), where longitudinal and lateral driving models can be specified, and evacuee behaviour (such as activation level, transition period) can also be fully controlled.

In the remainder of the paper, section II will describe the proposed model framework to investigate the transition phase on evacuation and its interaction with traffic control, where an agent-based modelling approach is adopted and the decision on driving and travelling behaviour is made. Section III will introduce the experimental study where the evacuation of a small Dutch region is described, and scenarios for sensitivity analysis and traffic control, and numerical indicators are illustrated. The simulation results and discussion are given in section IV. Finally, conclusions and future research directions are given in section V.

Methodology

In this section, the main research methodology is presented, including the proposed microscopic traffic simulation model framework, the choices of the proposed transition variables and travel behaviour, and the influence of traffic control measures on driving (travel) behaviour.

OTSim traffic simulation platform

This study applies an open-source and extendable software package: Open Traffic Simulator (OTSim) [7, 8] as the simulation environment. OTSim aims to support development of multi-scale and multi-modal traffic models. It provides a software environment that offers free to use knowledge and utilities, and can act as a starting point to create and develop new methods and models or to extend and improve existing models. It also offers a framework that enables the implementation of a wide range of traffic simulation models, from microscopic, macroscopic to meta-level, from motorized vehicles, track-bounded modes to pedestrian flows.

The middleware of the OTSim encompasses a network interface that processes and translates input data from external sources into a normalized format that can be used as input for all the other modules; a model and simulation interface that connects and combines different modules of traffic models into a work flow; and a visualization and evaluation interface that collects data and analyzes and presents the model results in a unified way.

Within the first prototype of this simulation framework, a Microscopic Open Traffic Simulation (MOTUS) [9] is developed and implemented as a simulator in the platform at a micro-level, which facilitates research into driving behaviour and its interaction with ITS applications. In this module, an agent-based modelling approach is implemented, which considers heterogeneous individual traveller response and interactions. Therefore, each vehicle (which is associated with one driver and/or some passengers) can be regarded as an agent. MOTUS contains a set of default driving models, including an extension of the Intelligent Driver Model (IDM) [10] and a lane change model with relaxation and synchronisation (LMRS) [11]. The car following IDM model is given in equation (1) where v is the current speed, Δv is the approaching rate (speed difference) to the predecessor, s is the net distance headway to the predecessor. Usually the acceleration exponent $\delta = 4$ is used.

$$\frac{dv}{dt} = a \cdot \min\left(1 - \left(\frac{v}{v_0}\right)^{\delta}, 1 - \left(\frac{s^*}{s}\right)^2\right) \quad (1)$$

$$s^* = s_0 + v \cdot T_{\min} + \frac{v \cdot \Delta v}{2\sqrt{a \cdot b}}$$

with a = maximum desired acceleration, b = maximum desired comfortable deceleration, s_0 = stopping distance, $T_{\min}$ = desired time headway, v_0 = desired speed. Evidence from [5, 12, 13] indicates that evacuation (emergency) situations have a significant influence on parameter values of driving behaviour, which leads to:

- substantial increase in maximum acceleration, maximum deceleration, and free speed;
- reduction in desired minimum time and distance headway;
- high speed variance due to diverse risk factors, such as incidents, specific threats;
- a tendency to disrespect traffic regulations and signals.

Therefore, these parameters in equation (1) are subject to change under emergence conditions, which will be quantitatively addressed in the next section.

The lane change LMSR model is structured around lane change desire. The desire (2) to change from lane i to lane j that arises from the different incentives is combined into a single desire:

$$d^{ij} = d_r^{ij} + \theta_v^{ij} \cdot \left(d_s^{ij} + d_b^{ij}\right) \quad (2)$$

There is a desire to follow a route (d_r), to gain speed (d_s), and to keep right (d_b), where the subscript b stands for bias to a particular side. The latter two are include with θ_v which is the level at which voluntary (discretionary) incentives are included. The specifications of these incentives can be found in [11]. Under evacuation situations, drivers might become more aggressive, have fewer tendencies to keep right or follow a route and higher desire to gain speed, etc. To consider this influence in the current model, one can recalibrate lane change desire thresholds and reformulate those incentives, and/or add new incentives/factors accounting for emergency conditions. For instance, the MOBIL model [14] has a "politeness factor" that could be used to model the change of drivers in different traffic conditions. This topic is subject to future research.

The main advantage of this driver model is simultaneously combining longitudinal and lateral driving decisions. In an earlier comparative study, MOTUS was proven to resemble traffic adequately at a macroscopic level, regarding the onset of congestion, the quantity of traffic flows and speeds [11]. This platform entitles full access and extendable modules, which allows us to better describe and capture changes of heterogeneous driving behaviour.

Transition Variable Definition

To investigate the influence of the transition phase, a transition behavioural variable, in this case the activation level (A) [15] is introduced into the driver model to account for the adaptation effects, which indicates how driving behaviour gradually or suddenly (in a certain time period) transforms from the normal status to the emergency status. In reality, drivers may slowly adapt to the surrounding driving behaviour (e.g., under emergency conditions), which implies a gradual change in activation level. Alternatively, there may be a sudden change in activation level due to a certain event, for instance, congestion setting-in and information acquirement from VMSs or in-car devices.

To investigate sensitivity, this one-dimensional state variable can be defined to be increasing (e.g., linear monotonously or step-wisely) over time from the beginning of simulation. And it will reach the full (or targeted) activation level after a certain period of transition time (T). The length of transition time can be influenced by several aspects, such as types of evacuation, levels of information penetration, patterns of infrastructures and driver characteristics. Here, qualitative

insights into transitions in driver behaviour allow specifying these variables, while (future) quantitative empirical analyses are needed to calibrate these variables. A step function hereof is assumed to accommodate the variables of activation level and transition time, with a predefined time-step (dt) over the total transition time (T). To consider heterogeneity, for each individual traveller from one specific traffic class, its activation level will be stochastically set based on the targeted activation level as a mean value with a small variance. Meanwhile, not all the travellers would switch to the emergency status, where some might maintain a normal driving style due to, for example, limited information acquirement. To this end, a penetration rate (P) of the traffic class with activation features is introduced to account for this aspect. This setting results in two driving classes: normal drivers and activated drivers. Normal drivers maintain their normal driving behaviour, while activated drivers can adjust their behaviour according to different transition variables. Hence, these three introduced variables describe the transition phase with respect to the share of individual drivers (P) who over time (T) express typical emergency driving behaviour to a certain degree (A).

Choices on Travel Behaviour during Evacuation

Within the OTSim platform, road networks can be created and/or adapted from an existing network model or from OpenStreetMap [16]. Traveller's decisions regarding how to travel/evacuate in road networks need to be specified. These decisions include the choice to evacuate, departure time choice, destination choice and route choice. The first two choices refer to travel demand modelling. In this research, trip demand can be adapted with the latest demographical data and demand profile can be variable over time, which is discussed in section III.B. Destination choice in this study would be embedded into route choice modelling. A short/no notice evacuation strategy [2] is employed, which assumes that travelers do not choose their destination upon departure, but instead tend to choose the route which leads them out of the threatened region as soon as possible. To this end, one super-destination zone is defined to connect all the potential existing points. Their virtual connections between super-zones and exit points are defined as zero costs for the route choice algorithm.

Following [2], pre-defined route sets or user-equilibrium assignment might be inappropriate for evacuation route choice modelling due to partial traveller compliance and the fact that the evolving traffic conditions cannot be fully anticipated. It is also suggested that hybrid route choice in combination with both instructed routes and en-route switches need to be considered. In this way, the influence of traffic management measures can be simulated and assessed. However, given that the effects of route choice behaviour and driving behaviour might be coupled in which the influence of driving behaviour on the network performance could not be fully reflected, in this research we let the route choice set to be prescribed and determined by a shortest path algorithm. Hence, this setting enables evaluating the interaction of different driving behaviour regarding prescribed evacuation routes. To be specific, we implement a link-penalty-based route choice set generation algorithm [17, 18], where link cost is based on (free-flow) link travel time. We let the empty network search for routes several times (e.g., 50 iterations). At each run,

Table 1. Relative change of selected driving parameters during transition phases

Symbol	Calibrated value in MOTUS	Normal	Emergency	Relative Change (RC)
a (m/s^2)	1.25*	0.94*	1.46	0.55
a_{urban} (m/s^2)	2.0	0.94	1.46	0.55
b (m/s^2)	2.09	0.87	0.97	0.11
b_{urban} (m/s^2)	3.5	0.87	0.97	0.11
v_0 (km/h)	123.7	108	127	0.18
$T_{\min}$ (s)	0.56	0.78	0.25	-0.68

*: The values in [5], however, pertain to mixed traffic. Cars as in MOTUS start somewhat higher.

penalties, such as an increase (e.g., 10%) to travel time, will be added to the previous-found route sets by the algorithm, so that a new route sets can be generated. In this way, a selection of reasonable route choice sets can be found. A logit model determines the probability of each route.

Experiment Setup

To understand the mechanism of different transition variables and their sensitivity on the network performance, an experimental study in the OTSim environment is performed. This experiment deals with a relatively small network: the Delft area in the Netherlands. First, parameters to describe driving behaviour are specified at transition phases. A detailed description on the experiment follows. The main purpose of this experiment is to investigate the network performance in case of the evacuation transition period and see if it provides new insights:

- Sensitivity analysis: what is the relation between the performance factors and transition variables (activation level, penetration rate, transition time)?
- Implication for DTM: are there any optimal operation regimes for traffic management in terms of both in-car control and roadside control measures? This will lead to the direction of our future work, where we can implement traffic control measures to influence those transition variables in favour of network performance

Driving Parameters at Transition Phases

In OTSim, the microscopic simulator MOTUS has been calibrated with detector data from a Dutch freeway (A20) for normal traffic situations [11], including desired vehicle accelerations /decelerations, desired speeds, headways, and model specific parameters to determine lane change incentives. Meanwhile, parameters in MOTUS to adjust for urban driving behaviour have been face-validated [19], such as maximum accepted acceleration/deceleration at intersections ($a_{\text{urban}}/b_{\text{urban}}$), conflicting safety factor, etc.

Obviously, drivers act and interact differently under emergency situations and more aggressive drivers are expected [5, 12]. In turn, the parameterized driver model requires a re-calibration procedure. However, this meets a main challenge given the limited field/empirical data to calibrate a model with the presence of emergencies. To solve this puzzle, we make use of the research outcome obtained from a driving simulator experiment [5]. In this experiment, the parameter values of a longitudinal driver model (IDM) have been estimated under
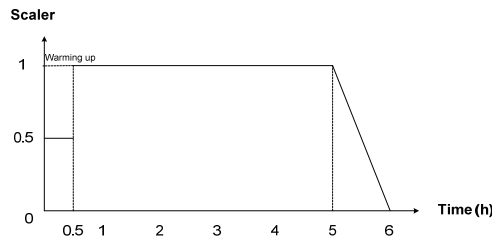
Fig. 1. Traffic demand profile for all simulation scenarios

	Transition Time (s)	Activation level	Penetration (%)
Reference	0	0	0
Testing levels	0	0	0
	600	0.33	33
	1800	0.66	66
	3600	1	100
	7200		

both nonemergency and emergency situations, including maximum acceleration (a), maximum deceleration (b), free-flowing speed (v_0), and desired time headway (T_{min}). The relative change of parameters between the two statuses can be mapped onto the current microscopic driver model to account for the difference between the normal status and the (fully-active) emergency status. Specifically, the calibrated values are multiplied with the relative change, as derived from the normal and emergency conditions in the driver simulator experiments. In total, six selected driving parameters are changed during simulation, as shown in Table 1. Due to limited research on lane change models under evacuation, the parameters related to the lane change incentives in MOTUS have not been changed in this study. Nonetheless, the current lane change LMRS model can be adjusted into evacuation situations to a certain extent by the influence of desired time headway. Specifically, desired time headway plays a role in determining gap acceptance for lane changing [11].

During simulations for the normal driver class, all the driving parameters remain the same throughout the simulation. Regarding activated drivers, their corresponding driving parameters will be altered according to the change of activation level. For instance, the activated acceleration (a_{act}) is calculated by: $a_{act} = a \cdot (1 + A \cdot RC)$. Note that these parameters are defined as mean values for each driver. Gaussian stochastic components are added for all individual drivers/travellers to consider heterogeneity. And traffic composition is fixed with 100% passenger cars.

Case Study Description

The Dutch Delft area is chosen as case study area. It is located in the western part of the Netherlands and contains both rural and urban areas. Possible threats might come from the west in case of a flood caused by dike-failure. A major freeway A13 passes through this area, which would be the main evacuation corridor for this area. For experimental studies, we
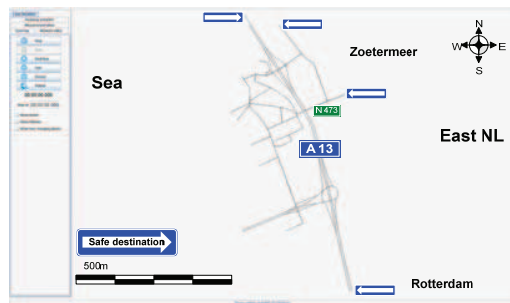

Fig. 2. Delft road network in the OTSim interface

convert an OmniTrans network [20] model of the city of Delft into the OTSim platform. The demand matrix in an evacuation condition is different from the normal daily traffic demand. In this study, the total traffic (vehicular) demand is estimated to be as one third of the total population in Delft (99108 inhabitants till 2013). And this demand (33036 vehicle units) is assumed to evacuate according to the demand profile as shown in Fig. 1. The total simulation time is a period of six hours, with the first half hour as the warming-up period to fill the network with background traffic (normal drivers). Constant demand at the beginning of transition phase is defined to isolate the impact of demand patterns in the transition phase. This demand profile allows the presence of both free-flow and congested traffic conditions in the network. The evacuees are travelling to the eastern part of the Netherlands, through one highway A13 (bi-direction 3 lanes) and one provincial road N473 (bi-direction 2 lanes) to the area of Zoetermeer.

The road network consists of freeways, provincial and urban arterials, leading to 134 links and 75 nodes, including 12 origins and 4 safe destinations (exit points). In Fig. 2, the whole study area is illustrated. As mentioned above, we employ a short/no notice evacuation scheme. Therefore, a super-destination zone is defined as it connects to the 4 exits, namely the two-exits of A13 and two two-lane roads towards to the eastern part of the country. Furthermore, all of the 22 junctions on urban area have been employed with fixed-time signalized controllers.

Design of Scenarios

In this experiment, one reference case is defined, namely a normal driving case without any activated drivers. For the sensitivity study, various combinations of the three transition variables are tested as shown in Table 2. Activation level and penetration rate are naturally bounded on the interval [0, 1]. Three testing levels (0.33, 0.66 and 1) allow to test direction and linearity in parameter sensitivity. As discussed above, transition time is uncertain and this requires further empirical underpinning. Here, a broad range is tested (0, 600, 1800, 3600 and 7200 s). There are in total 46 test scenarios (namely 5 transition times x 3 (non-zero) activation levels x 3 (non-zero) penetration rates + 1 reference case). Moreover, each scenario simulates over five fixed random seeds to account for stochastic effects (regarding vehicle generation and driving parameters).

Performance Indicators

To assess network performance in terms of different sensitivity scenarios, we define indicators for both the
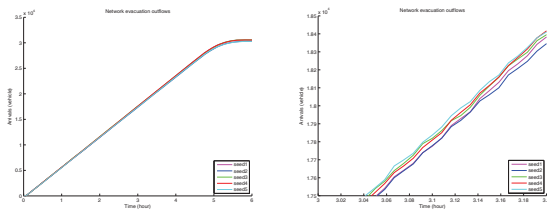
Fig. 3. Network outflows in the reference scenario of five stochastic runs (the right figure is the zoom-in of the left one).
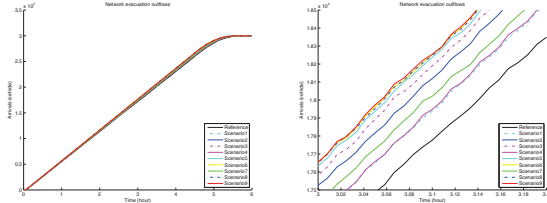

Fig. 4. Network outflows in scenarios with varying activation levels and penetration rates. Note that, to ensure fair comparison, the total demand in each scenario is normalized to 30000 vehicles.

aggregate performance and individual trip patterns. Overall, we employ arrival rates at destinations (the super-node), average travel time per vehicle. These indicators can reflect traffic flow operations during evacuation. For selected OD (origin-destination) trip patterns, we look at travel-time distributions (mean and standard deviation (std.)) of different driver groups. This can reflect traffic operations at OD levels in terms of different driver classes.

Result and Discussion

Fig. 3 shows the realized arrivals in the reference case in terms of five stochastic runs. Although the total demand in each run is slightly different, the arrival rate shows the same pattern. In addition, we notice that the clearance time in each run is of the same order. For the sake of brevity, in the following analysis, we only present the results from one of the five stochastic runs.

Sensitivity Analysis

Table 3 provides an overview of the network performance

Table 3. Network performance for diverse combinations of activation levels and penetration rates, at a fixed transition time (0s) (The selected OD relates to vehicles travelling from Delft south to the Rotterdam direction via A13 south.)

Sce.	Var. ActL/P	Ave. TT(s)	Clearance time (s) 100%	OD pair TT (normal drivers)		OD pair TT (activated drivers)	
				mean (s)	std.	mean (s)	std.
Ref.		288.52	19380	259.06	93.47	-	-
1	0.33/33%	267.06	19050	195.15	38.66	191.26	37.28
2	0.33/66%	231.88	18870	190.23	34.97	187.96	35.41
3	0.33/100%	196.96	18870	-	-	176.38	26.52
4	0.66/33%	251.43	19110	193.99	40.31	188.39	40.40
5	0.66/66%	196.41	18870	182.76	30.32	176.23	26.93
6	0.66/100%	185.37	18870	-	-	166.73	23.93
7	1.0/33%	248.86	19020	198.88	46.62	193.81	45.20
8	1.0/66%	192.35	18870	179.25	26.91	171.76	25.36
9	1.0/100%	181.87	18870	-	-	160.76	20.82

for the scenarios with varying both activation levels and penetration rates. The most important observation is that in all cases the network clearance time and average travel time decrease as the activation level increases and the penetration rate rises, compared to the reference scenario. In scenario 9, the average travel time decreases up to 35% compared to the reference case (181.87 s vs. 288.52 s). Overall, traffic flow operation and network performance are improving monotonously as increasing activation level and penetration rate. The activation penetration rate is more sensitive than the activation level. Similar observations can also be found from individual OD pairs. For a given OD trip, the travel times of both driver classes decrease in all cases; activated drivers experience a much lower travel time with a smaller variance, with respect to normal drivers.

Fig. 4 shows the arrival rates in terms of the nine scenarios listed in Table 3. This plot illustrates that increasing amount of activated driver class and activation level can lead to an earlier arrival of the total demand at safe destinations, as more throughput is achieved at the same time instant, and less delay is expected for the same arrivals. This is shown by the fact that the curves of arrival accumulated flow lies above the reference arrival curve (black solid line) maintaining a higher arrival rate. If there are more activated drivers with a higher activation level in the network, it indicates that travellers tend to accept smaller stopping distance and time headway, as well as behave more aggressively by larger acceleration/deceleration when performing a lane change and/or a car following movement. In turn, road capacities may increase. This also explains why the network clearance time under transition phases reduces and the average vehicle traffic time decreases, compared to the normal driving conditions (the reference scenario). This result confirms the pervious simulation-based observations in [4, 21], that emergency situations accompanied by an increase in acceleration and speed and a reduction in distance and time headway, can lead to increased road capacity and reduced network evacuation time, compared that under normal conditions.

Similar study has been conducted with varying transition time *T*. For the overall performance, the reduction of the average travel time in the scenarios with varying *T* is of comparable magnitude. We notice that scenarios with fast transition perform better than those with slow transition. Not surprisingly, this can be explained by the fact that activated drivers adapt to the targeted activation driving behaviour in a short time. Therefore, we can conclude that the gain in the network performance is mainly contributed by the transition period (before fully activated). However, the sensitivity of network performance to the transition time is lower than the other two variables.

Implication for traffic control and management

In the sensitivity study, we notice that network performance in terms of network clearance time and travel time is improving as the activation level increases, the penetration rate rises and the transition time reduces. In a case of a full activation level and 100% penetration with zero transition time, the improvement on travel time is up to 35%. In addition, network performance is more sensitive to the penetration rate of activated drivers than the other two variables. This implies that

with more evacuees expressing emergency driving behaviour, a lower network clearance time and travel time can be expected. In order to improve evacuation efficiency, traffic control and management should first target to increase such penetration rate by invoking more evacuees, and then try to increase the activation level of evacuees by changing their behaviour. In general, driving behaviour is a dynamic property of evacuees, and it can be influenced by many exogenous factors, such as evacuation time (short-non notice evacuation may induce aggressive driving behaviour), penetration rates of aggressive drivers (drivers may adapt to surrounding driving behaviour), evacuation information, etc. Therefore, traffic control measures can rely on information dissemination [22], for instance, in-car devices, speed-limit control, and VMSs, in a way that invokes preferred driving behaviour (smoothly adapted to high acceleration and speed, and small desired distance and time headway) and shortens the transition phase.

Conclusions

This paper is to pioneer the investigation of a transition phase in evacuation, which is characterised by a state of normal driving conditions to emergency driving behaviour. It has presented an open-source microscopic simulation model to assess the sensitivity of three transition variables (activation level, activated driver penetration and transition time) in terms of evacuation efficiency. The experimental results show that network performance can be improved with increasing activation level and penetration rate, and decreasing transition time. In addition, the sensitivity of the activation penetration rate is the highest among the three transition variables. And the variable of transition time has a least sensitivity. This implies that the increase of activated population to emergency driving behaviour would benefit evacuation efficiency. Interestingly, speed-limit control, variable message signs and in-car devices can be adopted to influence driving behaviour of evacuees in a way that leads to the efficient operation regime (low clearance time and average travel time). This topic is subject to our future research.

Future research will also focus on the investigation of lane change behaviour under evacuation via driving simulators. Based on which, more thorough analysis on the driving behaviour under evacuation transition can be taken forward.

Acknowledgment

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