https://dx.doi.org/10.1016/j.trc.2019.07.016

Optimisation of lane-changing advisory at the motorway lane drop bottleneck

Chunbo Zhang*[a, b, c], Nasser R. Sabar[b], Edward Chung[d], Ashish Bhaskar[b], Xiucheng Guo[c]

[a]School of Civil and Transportation Engineering, Hebei University of Technology, Tianjin, 300401, P.R. China

[b]Smart Transport Research Centre, Queensland University of Technology, Brisbane, 4000, Australia

[c]School of Transportation, Southeast University, Nanjing, 211189, P.R. China

[d]Department of Electrical Engineering, Hong Kong Polytechnic University, Hong Kong, China

*Corresponding author: zhangchunbochn@yeah.net

Abstract

Reduction in the number of lanes (lane drop) is common on motorways due to road design, incidents, or road maintenance, and it can be an active bottleneck if the traffic demand is high. If congestion occurs, the lane drop capacity will decrease 10-20%. In order to avoid capacity drop, this study analysed the reason and proposed lane-changing advisory control on the merge lane to distribute lane-changing using Cooperative Intelligent Transport Systems (C-ITS) technology. Further, this study used hyper-heuristic optimisation to obtain the lane-changing advisory proportion of each segment upstream of lane drop. Conditions of different traffic demands were analysed using the microscopic traffic simulation software AIMSUN and its Application Program Interface (API) function. Results indicated that the proposed lane-changing advisory strategy could reduce traffic congestion and obviously improve traffic efficiency. This study also analysed the effects with different proportions of connected vehicles and found that if the connected vehicle ratio is less than 20%, the lane-changing advisory has little impact on the lane drop performance, and that if the penetration rate is more than 50%, the gain in performance is marginal.

Keywords: Cooperative intelligent transport systems, lane drop, hyper-heuristic optimisation, lane-changing distribution, lane-changing advisory

1. Introduction

Due to road design, incidents or road maintenance, lane drop (reduction in the number of lanes) is a common site of motorways. If the traffic demand is high, the lane drop will be an active bottleneck, which leads to traffic congestion, long travel time, increasing environmental pollution and even reducing traffic safety. It has been confirmed that once congestion occurs, the capacity is lower than that just before the congestion, which is the so-called "capacity drop" phenomenon (Beritini and Leal, 2005). The capacity drop proportion is between 10% and 20% (Srivastava and Jin, 2016).

The main cause that leads to capacity drop is lane-changing, since vehicles on the shoulder lane are forced to make mandatory lane-changing to go through the lane drop site, which could lead to severe interference among vehicles (Laval and Daganzo, 2006). Researchers (Hadiuzzaman et al. 2013; Jin and Jin, 2014; Chen et al., 2014; Chen and Ahn, 2015; Zhang and Ioannou, 2015 and 2017) have proposed variable speed limit (VSL) in the upstream to reduce the flow into lane drop bottleneck which reduces the traffic density and increases the space among vehicles. Larger space among vehicles can alleviate lane-changing interference and can improve traffic efficiency. However, the speed limit must be low enough to reduce traffic density (Jin and Jin, 2015; Hadiuzzaman and Qiu, 2013) and the optimal results have shown to be lower than 20 km/h, which is generally not allowed on motorways in practice.

Cooperative Intelligent Transport Systems (C-ITS) supports the exchange of information between vehicles and infrastructures (vehicle to infrastructures (V2I or I2V), vehicle to vehicle (V2V)). C-ITS is expected to improve traffic safety, productivity and efficiency (Mai et al., 2016). This study takes advantage of C-ITS to propose a new lane-changing control strategy that improves the lane drop traffic efficiency.

This paper is organized as follows. First, the review of the literature is presented in section 2, which also includes discussions on the reasons leading to lane drop capacity drop. Thereafter, the proposed lane-changing advisory strategy based on C-ITS and the optimisation process for the proposed strategy is presented in section 3 and section 4, respectively. The proposed strategy is tested on a simulation test bed, the details for which are presented in section 5. Section 6 discusses the results of the analysis conducted on the simulation test bed. Finally, the paper is concluded in section 7.

2. Literature review

Bertini and Leal (2005) analysed the traffic of the bottleneck that arose near a motorway lane drop near London, U.K. using archived high-resolution loop detector data. The bottleneck's location and mean discharging flows were reproducible from day to day. It was shown that the bottleneck's capacity drop proportion was about 10%. Laval and Daganzo (2006) proposed a model by modelling each lane as a separate kinematic wave stream interrupted by lane-changing particles and applied the proposed model to a three-to-two motorway lane drop. Results showed that capacity drop proportion was about 10%. The research of Chamberlayne et al. (2012) showed that the capacity drop proportions are different with different locations. These results indicated that upon bottleneck activation, oscillations arose in the queue and propagated upstream. Flows measured at locations downstream of the bottleneck were not affected by these oscillations (Bertini and Leal, 2005). It provides strong evidence that the lane-changing can create voids and virtually occupy two lanes, which is the main cause of capacity drop. Also, the magnitude of capacity drop is related to the boundary and heterogeneity in accelerations of lane-changing vehicles (Laval and Daganzo, 2006; Srivastava and Jin, 2016; Chamberlayne et al., 2012), the bottleneck area's space-mean speed and driving reaction time (Yuan et al., 2017).

In order to overcome the capacity phenomenon, many researchers used VSL to improve the bottleneck's traffic efficiency. A new VSL scheme was developed based on the Kinematic Wave theory to increase motorway bottleneck discharging flow (Chen et al., 2014; Chen and Ahn, 2015). The key principle was to impose VSL control some distance upstream of a bottleneck to starve the inflow to the bottleneck and dissipate the queue. Some analytical models, like Lighthill-Whitham-Richards (LWR) model and the link queue model (Hadiuzzaman et al., 2013; Jin and Jin, 2015), were developed to represent drivers' response to updated speed limits, and speed changing with respect to changeable speed limits. However, Zhang and Ioannou (2015 and 2017) indicated that most existing VSL controllers showed significant benefits in macroscopic analysis but little improvement in microscopic simulations in terms of traffic mobility. Besides, the speed limit value is too small even less than 20 km/h (Jin and Jin, 2015; Hadiuzzaman and Qiu, 2013), which is not allowed on the motorway in practice.

As the lane-changing is the main caused of capacity drop, lane-changing advisory is another tool to improve the bottleneck's traffic efficiency. Gong and Du (2016) used the lane-changing advisory control through providing an advance warning for lane change necessity to perform systematic lane change management, which encourages smooth mandatory lane change (MLC) occurring at proper locations to mitigate the negative effects of MLC manoeuvres on traffic flow nearby off-ramp. Results showed that the corresponding capacity drop and traffic oscillation could be efficiently mitigated. Mai et al. (2016) investigated a lane-changing advisory application based on C-ITS for weaving vehicles in weaving sections, and the evaluation revealed that the proposed lane-changing advisory has the potential to significantly improve delay. Hayat et al. (2016) thought that the lane-changing advisory holds significantly potential to mitigate congestions in freeway merge areas, and recommended that the advisory messages should be direct and clear. Schakel and Arem (2014) presented an in-car advisory system including lane-changing advisory. This advisory system aimed for an optimal lane distribution in high flow conditions, decreasing the chance of spillback by advising drivers away from side lane, and a reduction in the capacity drop by advising drivers to maintain a short (but safe) headway at the end of congestion. The results indicated that the capacity drop was mainly reduced. These verified that the lane-changing advisory control is very effective to mitigate the traffic congestion at the bottleneck location.

However, there is no effective lane-changing advisory control for the motorway lane drop section. In order to fill this gap, it is inevitable to propose a corresponding control method for the lane drop bottleneck. With C-ITS, it is possible to send information to each vehicle and advise different vehicles to make lane-changing at different locations. This offers the opportunity to optimise the lane-changing distribution to improve traffic efficiency and it is the foundation of this study.

3. C-ITS based lane-changing advisory strategy for the lane drop section

As analysed in the literature review, the main reason that leads to capacity drop at lane drop location is that many vehicles in the leftmost lane make lane-changing near the bottleneck (**Figure 1(a)**). The high intensity of lane-changing could lead to lower speed. The lane-changing vehicles with lower speed can create voids in traffic streams, which can reduce discharging flow (Laval and Daganzo, 2006). Hence it is inevitable to propose a strategy to distribute lane-changing (**Figure 1(b))** and it will distribute the affection on traffic efficiency just near the bottleneck. The voids created by upstream lane-changing vehicles may be filled by downstream lane-changing vehicles with higher insertion speed, which can avoid other voids caused by themselves. As a result, the overall lane drop section traffic efficiency will be improved. The strategy proposed here is inspired by Mai et al. (2016) and the specific flow chart is shown in **Figure 2** and explained as follows.

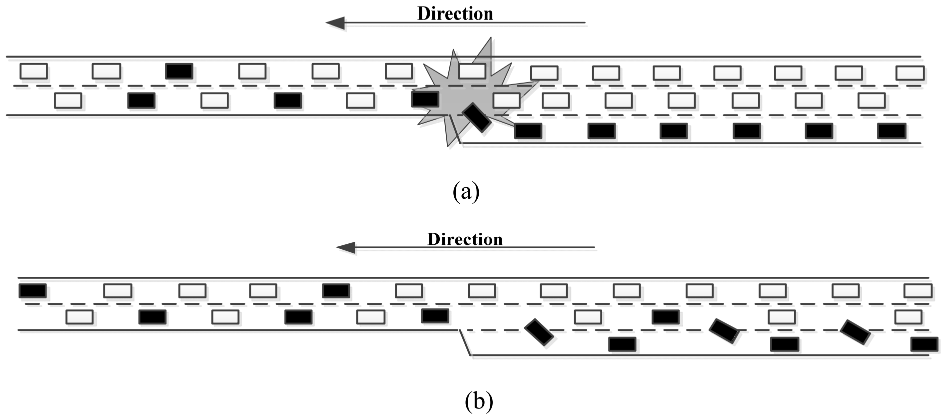


Figure 1 Lane-changing near bottleneck (a) without control (b) with lane-changing control (left hand driving)

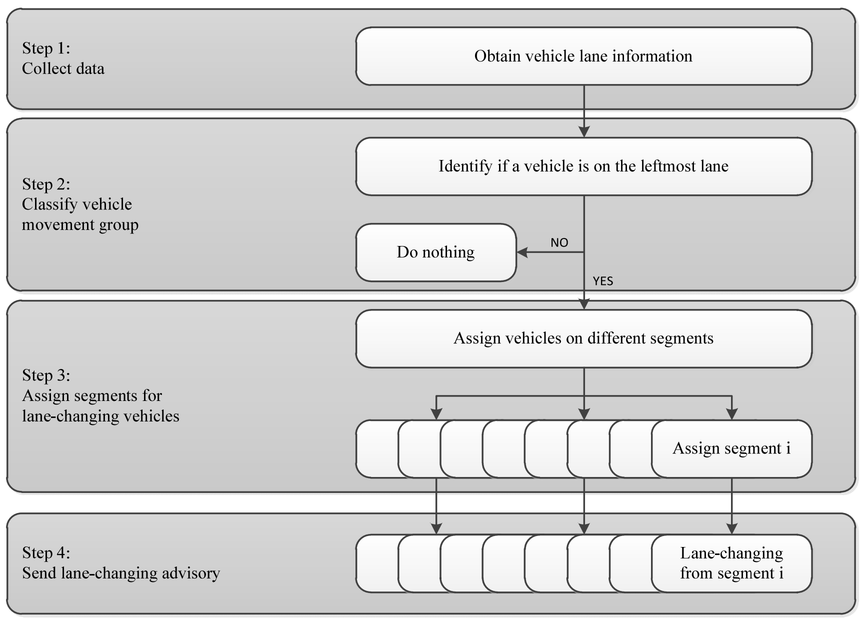


Figure 2 Flow chart of lane-changing advisory for lane drop section for left hand driving. For right hand driving the term 'leftmost' should be replaced with 'rightmost'

Step 1. **Collect data.** In this step, collect the vehicle lane information at the location L meters upstream of the bottleneck through V2I communications. Assuming Road Side Units (RSU) located in the upstream of the lane drop section, vehicles equipped with C-ITS capability would send their lane information, as shown in **Figure 3**.

Step 2. **Classify vehicle movement group**. Classify the vehicles in the leftmost lane (rightmost lane if right hand driving) into lane-changing (advisory) vehicles and the vehicles in the middle lane or rightmost lane (leftmost lane if right hand driving) into non-lane-changing vehicles according to their lane information. For the non-lane-changing vehicles, no further actions would be done. For lane-changing vehicles, several actions will be conducted as described in Step 3. For example, the vehicle 1 in the leftmost lane in **Figure 3** has to make lane-changing to go through the lane drop site and it is classified as the lane-changing vehicle; the vehicle 2 in the middle lane and the vehicle 3 in the rightmost lane do not have to make lane-changing and they are classified as non-lane-changing vehicles.

Step 3. **Assign segments for lane-changing vehicles**. This step assigns one segment for each lane-changing vehicle, from which they may start to perform a lane change. In this study, the $\boldsymbol{L}$ meters upstream of the lane drop section is divided into ***N*** segments and the length of each segment is Δx meters as shown in **Figure 3**. Lane-changing proportion of each segment is generated by the proposed optimisation method (described in Section 4) for which the goal is to minimize the traffic delay. The main goal of the optimisation method is to find the appropriate advisory lane-changing proportions for each segment that can satisfy all constraints and minimise (or maximize) the defined objective function. In this work, minimizing the total travel time (TTT) is selected as our objective function as described in Equation (1), which is equivalent to maximize the throughput of the bottleneck section.

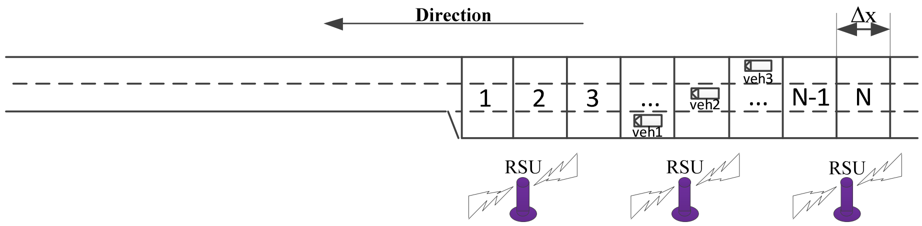


Figure 3 RSUs near the lane drop bottleneck

$$\min\ TTT = \sum_i \sum_j \Delta t * m_{i,j} \tag{1}$$

Where, TTT denotes the Total Travel Time, Δt is the simulation time interval, $m_{i,j}$ is the number of vehicles at section j at time interval i, and it can be obtained using the Application Programming Interface (API) function of AIMSUN (a microscopic traffic simulation software).

The control variables are the lane-changing advisory proportions of each segment and the constraints are shown in Equations (2) and (3).

$$\sum_j x_j = 1 \tag{2}$$

$$0 \le x_j \le 1 \tag{3}$$

Where, x_j is the lane-changing advisory proportion of segment j.

Figure 4 C-ITS based text message example (source: Transport for NSW, 2015)

Once the lane-changing proportions have been generated, we assign vehicles to each segment in a random manner according to the proportion sizes as follows: generates a random number between *0* and *1* for each vehicle. If the random number is between 0 and the size of the proportion of the first segment, assign the vehicle into first segment; if the random number is between the cumulative proportions of segment ***i-1*** and segment ***i***, segment ***i*** is assigned to the vehicle and so on.

Step 4. **Send lane-changing advisory**. Send each vehicle a lane-changing advisory through I2V communications to indicate where they may make lane-changing. This strategy provides advisory control and does not force lane-changing. For example, if vehicle is assigned to segment ***N***, it may execute lane-changing at segment ***N*** or further downstream when a suitable gap is available. This advisory control restricts vehicle lane-changing until it reaches its assigned segment, at which point the AIMSUN lane-changing model controls the vehicle lane-changing behaviours (Mai et al., 2016).

The lane-changing vehicles will receive lane-changing messages in the form of text and sound, which is currently implemented in many C-ITS applications in real-world, such as in Japan (Fukushima, 2011; Kanazawa et al., 2010). An example where the text is displayed is presented in **Figure 4** (Transport for NSW, 2015). For this study, two kinds of messages are used:

- 'Distance until making lane-changing' (distance countdown to the lane-changing reference location);
- 'Please seek gap to make lane-changing' (this message alerts drivers to make lane-changing where there is a suitable gap).

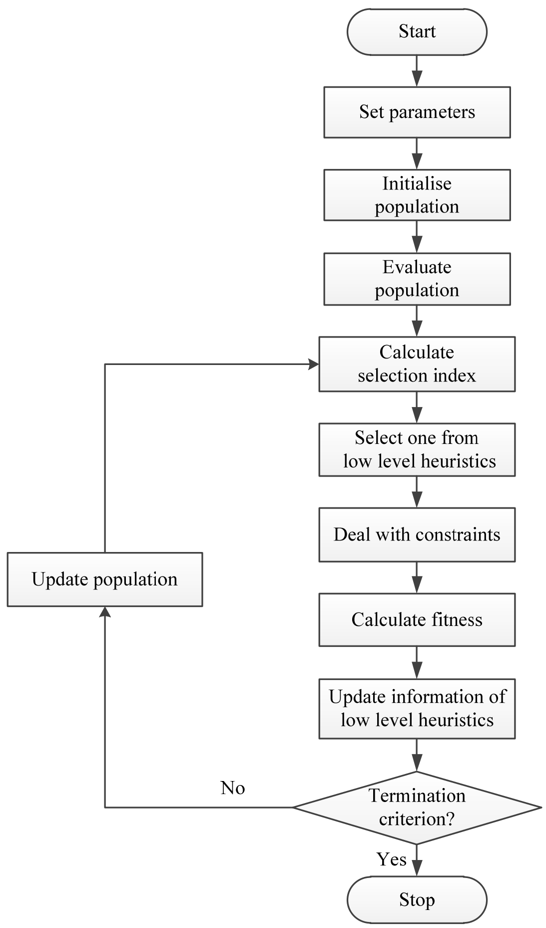


Figure 5 The flowchart of hyper-heuristic

4. The proposed optimisation method

The lane-changing proportion generation process (described in Step 3, Section 3) can be formulated as a continuous optimisation problem. The goal is to minimise the objective function (Equation (1)). The uncertainties in the traffic demand prohibit the use of analytical methods in an online manner. The lane-changing advisory includes N proportions, each of which can be any value between 0 and 100%. This could be very difficult to find satisfactory results using simple heuristic method, such as Genetic Algorithm. In this work, we propose a hyper-heuristic method to generate the lane-changing proportion. Hyper-heuristic (Hyper-heuristic, 2017) is a heuristic based search algorithm that reacts to the problem changes through using several heuristics in an adaptive manner (Sabar et al., 2015). The main idea is to combine the strength of several heuristics in a unified framework to efficiently solve a given problems. A traditional hyper-heuristic method consists of two components known as the high-level strategy and the low-level heuristics. The high-level strategy manages the selection of which heuristic should be applied at each decision point. The low-level heuristics encompass a set of heuristics to generate the lane-changing proportion. At each iteration of the solving process, the high level strategy of the hyper-heuristic method adaptively select one heuristic from the given set of heuristics. The selected heuristic will be used to generate a new lane-changing proportion. Next, the hyper-heuristic method calls the objective function and updates the parameters. This process is repeated for a pre-defined number of iterations.

In this work, we propose an evolutionary hyper-heuristic method to deal with the lane-changing proportion generation process. It uses a population of solutions to effectively explore the search space and utilises a various set of mutation and crossover operators as low-level heuristics. Each solution in the population is represented as one-dimensional array as shown in **Table 1**. The flowchart of the proposed hyper-heuristic method is shown in **Figure 5** (the detail of each step is shown in the **Appendix**).

Table 1 An example of lane-changing advisory proportions

Seg1	Seg2	Seg3	Seg4	Seg5	Seg6	Seg7	Seg8
10%	20%	10%	10%	20%	10%	10%	10%

5. Simulation test bed

The analysis of this study is based on the commercially available microscopic traffic simulation software, AIMSUN v8.1.3. The hardware of the simulation bed is that the processor is Intel(R) Core(TM) i7-4810MQ CPU @ 2.80GHz 2.80 GHz and the Installed memory (RAM) is 16.0 GB. The three-to-two lane drop network is built in AIMSUN, the same as that shown in **Figure 3** with $N=8$ and $\Delta x=50$ meters. The model is calibrated before further analysis. The calibration process is changing model parameters and comparing model outputs with a set of real data iteratively to reflect the observed local traffic and driving behaviour conditions. As analysed in Section 2, the main cause of capacity drop at lane drop bottleneck is lane-changing (Laval and Daganzo, 2006). As lane-changing leads to low speed, there will be some void in the front of the lane-changing vehicles and the acceleration rate will determine the capacity drop proportion. So the acceleration rate is an important parameter that needed to be calibrated (Yuan et al., 2017). Further, the parameter gap in AIMSUN can influence the vehicle headway, and the parameter clearance in AIMSUN means the minimum distance between stopped vehicles. They are related to the lane drop capacity and these two parameters are also selected as calibrating parameters. In order to guarantee the calibrated model can reflect real traffic conditions, the mean of clearance, acceleration rate and gap are limited to the range of 0~3 m, 2~4 m/s^2 and 0~3 s respectively.

Table 2 Lane drop discharging flow rate before and after congestion on M4

Day	Flow immediately prior to the queue		Average discharging rate		Drop percent (%)
	Rate (vehicles/h)	Duration (h:min:s)	Rate (vehicles/h)	Duration (h:min:s)	
Day1	3690	0:17:50	3300	2:22:06	10.6
Day2	3690	0:14:45	3300	2:19:25	10.6
Day3	3750	0:11:57	3500	1:33:32	6.7
Day4	3840	0:08:07	3430	2:06:09	10.7
Day5	3510	0:13:12	3150	4:52:22	10.3
Mean	3700	--	3340	--	9.7

The real data, shown in **Table 2**, used to calibrate these parameters are from a three-to-two lane drop on the M4 motorway near London, UK (Bertini and Leal, 2005). In order to get the maximum discharging flow before and after congestion, the discharging flow of two normal lanes is the same as the flow immediately prior to the queue, and the discharging flow of three-two lane drop bottleneck after queue formation is the same as the average discharging rate after congestion. The default and calibrated values of three parameters (Clearance, Acceleration rate and Gap) in AIMSUN are shown in **Table 3**. The calibration results of 20 replications, which have different random seeds, using the real data of Day 1, Day 2 and Day 3 are shown in **Table 4**. The validation results using the real data of Day 4 and Day5 are shown in **Table 5**. According to the t-values, the calibrated model is able to simulate observed traffic phenomenon well. Hence, the calibrated model is good enough to use for further analysis.

Table 3 Default and calibrated values of parameters in AIMSUN

	Default values			
	Mean	Deviation	Minimum	Maximum
Clearance (m)	1.00	0.30	0.50	1.50
Acceleration rate (m/s^2)	3.00	0.20	2.60	3.40
Gap (s)	0.00	0.00	0.00	0.00
	Calibrated values			
	Mean	Deviation	Minimum	Maximum
Clearance (m)	1.10	0.30	0.60	1.60
Acceleration rate (m/s^2)	3.80	0.20	3.40	4.20
Gap (s)	2.40	0.10	2.20	2.60

* Only car is considered in this study; other vehicle types are not included, such as trucks.

Table 4 Discharging flow with default and calibrated parameter values

	Results with default parameter values				
	Replications	Mean	Standard deviation	[95% confidence interval]	t-value
Flow prior to queue	20	5107.6	7.88	[5103.9 51113]	172.9***
Discharging rate after queue	20	3780.2	44.26	[3759.5 3800.9]	6.1*
	Results with calibrated parameter values				
	Replications	Mean	Standard deviation	[95% confidence interval]	t-value
Flow prior to queue	20	3713.6	15.61	[3706.3 3720.9]	-0.2
Discharging rate after queue	20	3334.0	42.52	[3314.1 3353.9]	0.5

*, ** and *** denote significant level 0.05, 0.01 and 0.001, respectively.

Table 5 Validation results of discharging flow with calibrated parameter values

	Results with calibrated parameter values				
	Replications	Mean	Standard deviation	[95% confidence interval]	t-value
Flow prior to queue	20	3713.6	15.61	[3706.3 3720.9]	0.2
Discharging rate after queue	20	3334.0	42.52	[3314.1 3353.9]	0.3

*, ** and *** denote significant level 0.05, 0.01 and 0.001, respectively.

6. Simulation result discussion

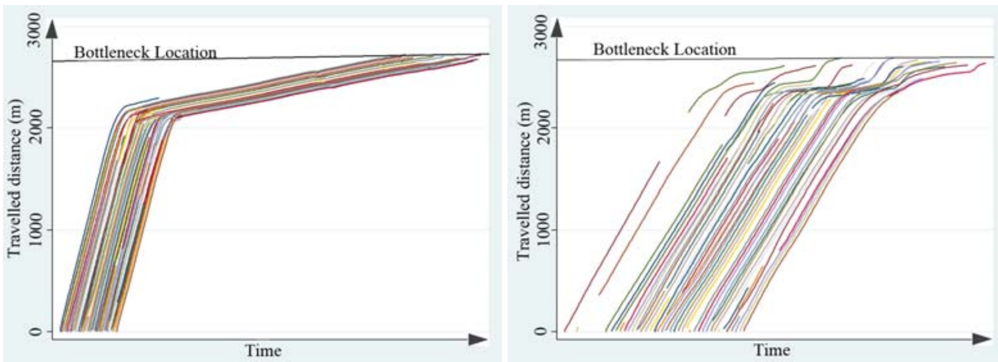
Simulations under high, middle and low traffic demand (4000, 3600 and 3200 veh/h respectively) were run. High traffic demand of 4000 veh/h is above the 2 lane capacity before flow breakdown, middle traffic demand (3600 veh/h) is between the 2 lane capacities before and after flow breakdown, and low traffic demand (3200 veh/h) is that lower than dropped capacity. For each scenario, there are 20 replications to account for the randomness. The warm up time and the simulation time for each scenario is 10 minutes and 30 minutes, respectively.

6.1. Results with 100% connected vehicles

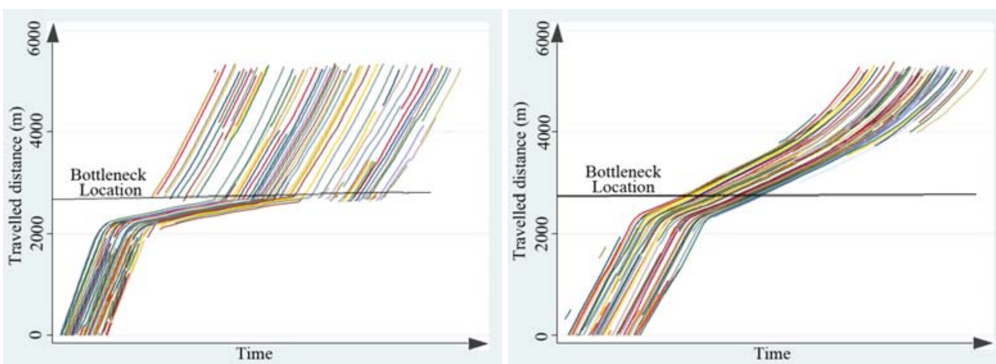
Table 6 Optimised lane-changing advisory distribution of each segment for 100% connected vehicles

Traffic demand(veh/h)	TTT (veh-mins) *	Flow (veh/h)		Seg1 (%)	Seg2 (%)	Seg3 (%)	Seg4 (%)	Seg5 (%)	Seg6 (%)	Seg7 (%)	Seg8 (%)
4000	7342 (390)	3728	Optimised	39	9	16	0	0	7	13	16
	11117 (639)	3310	Base case	Without lane-changing advisory							
3600	4949 (466)	3598	Optimised	17	20	19	7	14	3	4	16
	8150 (759)	3312	Base case	Without lane-changing advisory							
3200	3353 (206)	3210	Optimised	17	25	15	0	1	0	19	23
	3389 (232)	3236	Base case	Without lane-changing advisory							

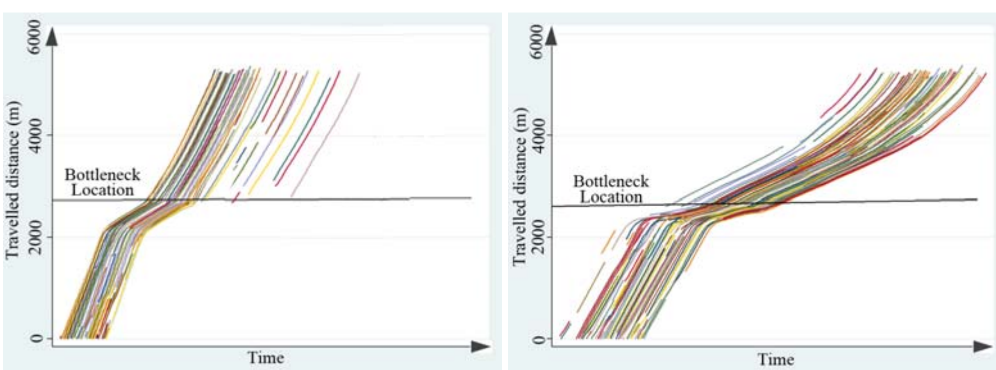
* The values in brackets are the Standard Deviation of TTT.



(a) Leftmost lane without control (b) Leftmost lane with control



(c) Middle lane without control (d) Middle lane with control



(e) Rightmost lane without control (f) Rightmost lane with control

Figure 6 Trajectories of vehicles in each lane with and without control under traffic demand 4000 veh/h

The optimisation and the base cases without lane-changing advisory results are shown in **Table 6**. For high traffic demand (*4000 veh/h*), the TTT is reduced by 34% from *11117 veh-mins* to *7342 veh-mins*. Further, the flow is also increased from *3310 veh/h* to *3728 veh/h* (*13%)*. These performance indicators showed that the optimised lane-changing advisory control can avoid the capacity drop at lane drop location and improve the lane drop traffic efficiency. For middle traffic demand (*3600 veh/h*), the TTT is reduced by 39% from *8150 veh-mins* to *4949 veh-mins*. Further, the flow is also increased from *3312 veh/h* to *3598veh/h* (9%). These performance indicators showed that for middle traffic demand, the optimised lane-changing advisory control can also improve lane drop traffic efficiency. For low traffic demand (*3200 veh/h*), the TTT changes from *3389 veh-mins* to *3353 veh-mins (1%)* and the flow changes from *3236 veh/h* to *3210 veh/h (0.8%)*. Neither the TTT nor the flow has substantial improvement. These performance indicators showed that it is not necessary to control the lane drop traffic in practice if the traffic demand is lower than the reduced capacity.

The reason why the optimised lane-changing advisory control can improve lane drop traffic efficiency is that lane-changing advisory can distribute the lane-changing of vehicles. The distribution of vehicle lane-changing can reduce the negative effect on traffic efficiency at the fixed location near lane drop. That is to say, the lane-changing advisory control can thus avoid lane-changing concentration phenomenon, which is the main cause of capacity drop at the lane drop bottleneck (Laval and Daganzo, 2006). The mechanism of capacity drop is due to the voids created by the lane-changing vehicle with lower insertion speed from leftmost lane, which can reduce the discharging flow. As shown in **Figure 6(c) and Figure 6(e),** the trajectories without control change from compact to sparse, especially in the middle lane, which indicated dropped capacity. On the other hand, the lane-changing advisory control can smooth the lane-changing vehicles and improve the traffic efficiency as shown in **Figure 6**. The trajectories in middle and rightmost lane keep compact as shown in **Figure 6(d) and Figure 6(f),** which keeps the throughput high. Besides, the insertion speed (the speed in leftmost lane) becomes higher compared to that without control as shown in **Figure 7,** in which the speed of each lane near the bottleneck is shown. This verified that the voids created by upstream lane-changing vehicles can be filled by downstream lane-changing vehicles with higher insertion speed, which can avoid other voids caused by themselves.

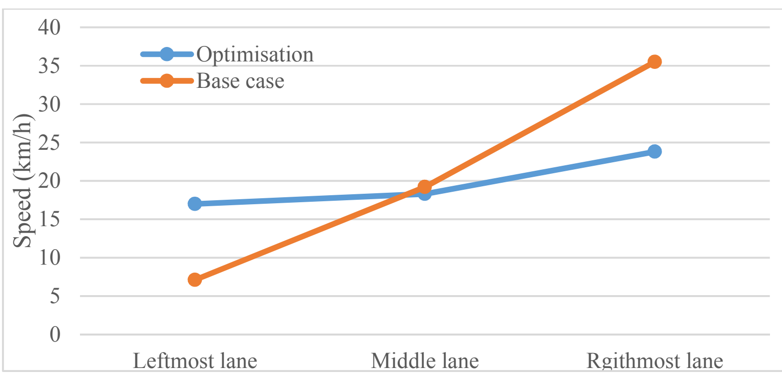


Figure 7 The average speed of each lane with and without control under traffic demand 4000 veh/h

For the specific lane-changing advisory proportion, if many vehicles are advised to make lane-changing just near the lane drop location, congestion may still occur and it cannot improve the traffic efficiency. On the other hand, if most lane-changing is advised in the far upstream of the lane drop location, the congestion can be avoided and the traffic efficiency can be improved, but the leftmost lane just upstream to the lane drop location will be underutilised. This can lead to an increase in TTT. Hence the optimal traffic efficiency is obtained between these two conditions (i.e. concentration of lane changes just upstream and far upstream of lane drop).

The interplay between lane changes at locations A and B as shown in **Figure 8** creates opportunities for vehicles on the leftmost lane to merge into the middle lane. When vehicles start looking for gaps at location A, they prevent vehicles wanting to change lane at location B downstream. This reduces the influx of vehicles looking for gaps to merge near the bottleneck. This mechanism is similar to upstream gating or metering. The benefit of this two sections lane-changing strategy is that the leftmost lane is fully utilised whilst the upstream lane changes regulate the intensity of lane changes at the bottleneck.

If all vehicles in the leftmost lane are advised to make lane-changing at the same location, the TTTs are shown in **Table 7** and **Figure 9**. The best scenario is advising all vehicles to make lane-changing at segment 3 which is 150 m upstream of the bottleneck (**Figure 9**). If all vehicles are advised to make lane-changing near the bottleneck such as at segment 1 then the capacity drops leading to increasing TTT; if all vehicles are advised to make lane-changing far upstream from the bottleneck such as segment 8 then the leftmost lane is underutilised from segment 1 to segment 7. So advising lane-changing at segment 3 to all vehicles is a good option. However, it is outperformed by the optimised lane-changing advisory control. This verifies that the optimised control scenario is better than scenario No. 3.

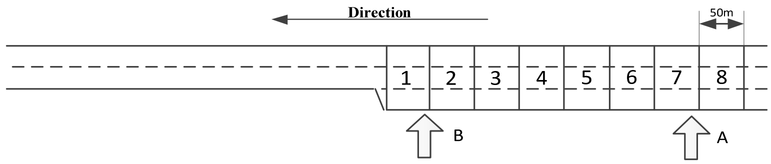


Figure 8 Lane-changing at different locations

Table 7 Different lane-changing advisory control scenarios under traffic demand 4000 veh/h

Scenario No.	Seg1 (%)	Seg2 (%)	Seg3 (%)	Seg4 (%)	Seg5 (%)	Seg6 (%)	Seg7 (%)	Seg8 (%)	TTT (veh-mins)	Flow (veh/h)
1	100	0	0	0	0	0	0	0	8898	3500
2	0	100	0	0	0	0	0	0	7959	3659
3	0	0	100	0	0	0	0	0	7872	3715
4	0	0	0	100	0	0	0	0	7922	3722
5	0	0	0	0	100	0	0	0	8023	3715
6	0	0	0	0	0	100	0	0	8148	3712
7	0	0	0	0	0	0	100	0	8228	3712
8	0	0	0	0	0	0	0	100	8346	3714
Optimised	39	9	16	0	0	7	13	16	7342	3728

The reason why the optimised control scenario is better than scenario No. 3 can be explained using fundamental diagrams. The traffic states of Scenario No. 3 and Optimised Scenario are shown in **Figure 10(a)** and **Figure 10(b)**, respectively. The fundamental diagrams of three lanes (red line), three lanes with lane-changing (purple line for less lane-changing, blue line for advisory lane-changing, black line for much lane-changing), and two lanes (green line) are shown in **Figure 11.** Jin (2010) indicated that the lane-changing vehicle using both its current and target lanes could cause effective additional density. The additional density can reduce traffic flow. So it is reasonable to set different free-flow speeds for different conditions and to use the lines between two-lane and three-lane fundamental diagrams to represent the different lane-changing three-lane fundamental diagram.

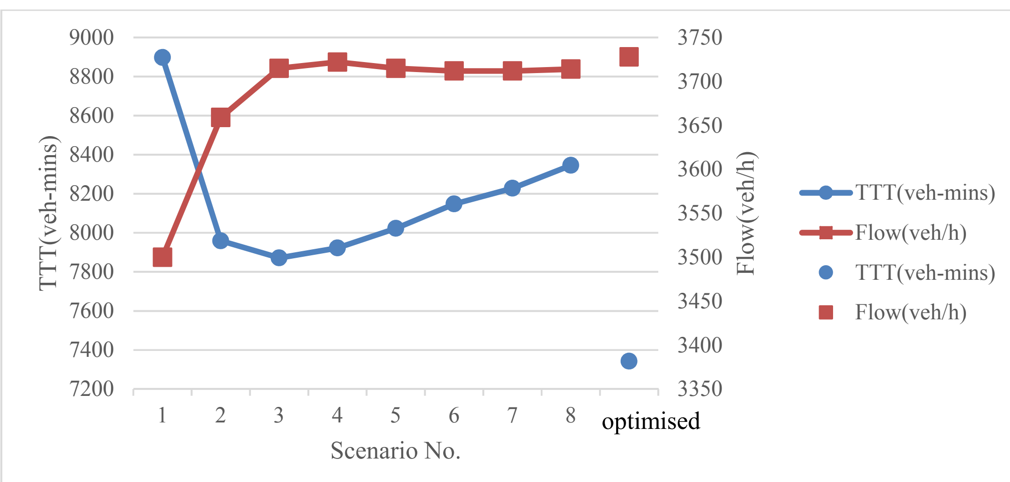


Figure 9 The TTT under different control scenarios

For scenario No. 3, all vehicles are advised to make lane-changing at segment 3, and traffic states from upstream to downstream are three-lane free-flow state G, three-lane congested flow C, three-lane flow with less lane-changing state D, and two-lane free-flow state B respectively as shown in **Figure 10(a).**

For the Optimised Scenario, traffic states from upstream to downstream are three-lane free-flow state G, three-lane congested flow C, discretionary lane-changing state F, three-lane flow with more lane-changing state E and two-lane free-flow state B respectively shown in **Figure 10(b).**

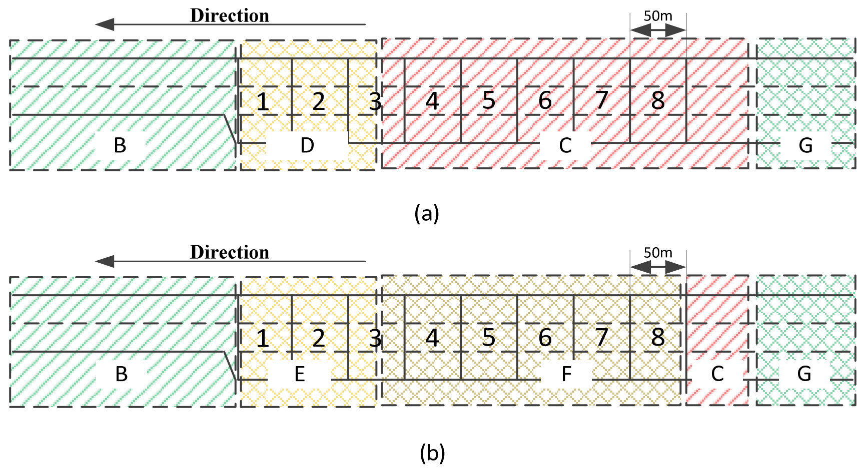


Figure 10 Traffic states of a) control scenario No. 3 and b) optimised control

For both control scenarios, the throughputs are almost the same (**Table 7**) and the section from upstream to segment 3 can be regarded as one link. As the throughputs and traffic demands (4000 veh/h) are almost the same, and the initial condition is the same, the vehicle number in the link for both control scenarios are the same. This means the flow and density of the link for both control scenarios are the same. Hence the space-mean speed of the link for both control scenarios are the same. The states of the downstream are all state B with same speed. So the TTT difference between these two control scenarios is due to the state difference of the section from segment 3 to bottleneck location, which is state D and state E, respectively as shown in **Figure 10(a)** and **Figure 10(b).** From **Figure 11**, it is obvious that the speed of state E is higher than that of state D, that is to say, the optimised control scenario is better than advising all vehicles to make lane-changing at segment 3.

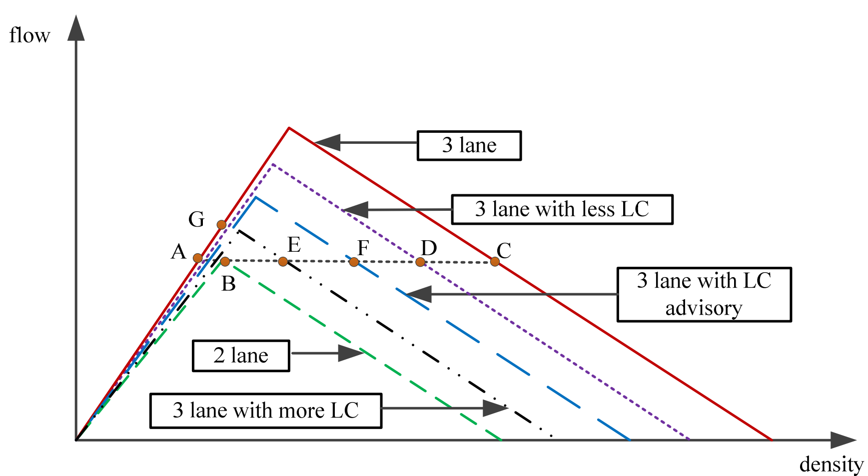


Figure 11 Fundamental diagrams of the lane drop

6.2. Results with different proportions of connected vehicles

The proportion of connected vehicles will change with more vehicles with connectivity (communication capability), and it is necessary to consider the condition not all vehicle are connected. So different proportions of connected vehicles are specially analysed in the simulation test bed using the proposed optimisation method. The TTT and flow for different proportions of connected vehicles are shown in **Figure 12**.

From **Figure 12**, the TTT decreases and the flow increases respectively as the connected vehicle ratio increases. This indicates that the more the connected vehicles there are, the better the lane drop traffic efficiency will be.

From **Figure 12**, there are two turning points, one is connected vehicle ratio at 20% and the other at 50%. That is to say, if the connected vehicle ratio is less than 20%, the lane-changing advisory has negligible impact on the lane drop efficiency and if the connected vehicle ratio is more than 50%, the gain in performance is marginal.

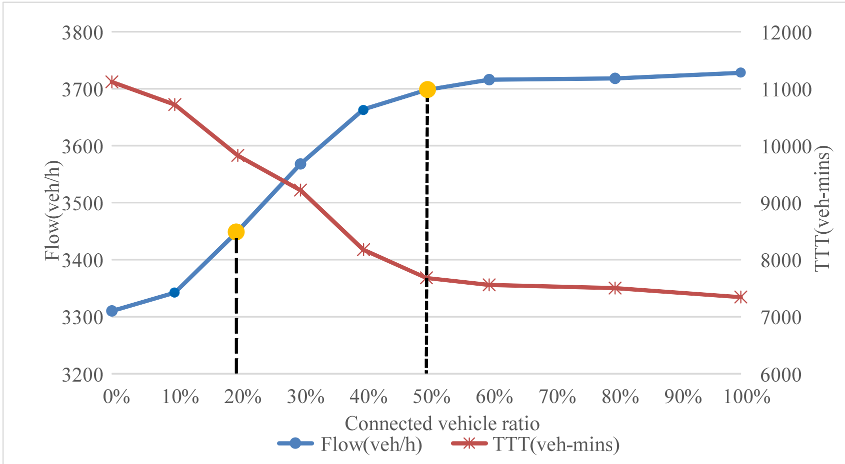


Figure 12 TTT and flow with different connected vehicle ratios under traffic demand 4000 veh/h

7. Conclusion

As the main reason of capacity drop of lane drop section is that most vehicles make lane-changing just near the lane drop location, this study proposed a lane-changing advisory control to distribute lane-changing vehicles and determined the lane-changing advisory proportions of each segment using the hyper-heuristic optimisation. The results indicated that the strategy proposed by this study can improve lane drop traffic efficiency significantly. The contribution of this study includes:

- This study proposed the lane-changing advisory control for lane drop section using the C-ITS technology, which makes it possible to exchange between vehicles (V2V) and between vehicles and infrastructures (V2I);
- The hyper-heuristic optimisation was used to optimise the lane-changing advisory proportion based on microscopic traffic simulation software AIMSUN and its API function;
- This study found that under high and middle traffic demand about 60% of the vehicles in the shoulder lane should be advised to make lane-changing at about 100 meters upstream of the lane-drop bottleneck and about 40% of the vehicles should be advised to make lane-changing 400 meters upstream to improve the traffic efficiency by the utmost extent;
- Different proportions of connected vehicles were analysed to reflect the upcoming uptake of connected vehicles. If the connected vehicle ratio is less than 20%, the lane-changing advisory has negligible impact on the lane drop efficiency and if the connected vehicle ratio is more than 50%, the gain in performance is marginal.

Though the strategy proposed can improve the lane drop efficiency, only the lane-changing advisory control in the leftmost was analysed and the lane-changing in other lanes was not considered. The authors will analyse the lane-changing advisory control on each lane upstream of lane drop in the future.

Acknowledgement

The first author was a visiting student during November 2016 to October 2017 at the Smart Transport Research Centre of Queensland University of Technology supported by the China Scholarship Council (CSC). The authors thank the editors and reviewers for their important comments and suggestions, which helped to improve the paper completely.

Appendix Hyper-heuristic method process

The hyper-heuristic method detail of each step are as follows:

- **Step 1:** *Set the parameters*. The hyper-heuristic optimisation parameters are initialised in this step. They are:
  - Maximum number of iterations – indicates when hyper-heuristic search process will be stopped.
  - Population size – indicates the number of solutions to form the population.
- **Step 2:** *Initialise population.* In this step, each individual of initial population is randomly initialised. We also verify that the generated solution satisfies the constraints presented in Equations (2-3).
- **Step 3:** *Evaluate population.* The fitness of each individual in the population is calculated using Equation (1).
- **Step 4:** *Calculate selection index.* This step determines which heuristic should be used. It calculates the index of all heuristics and selects the one that maximise Equation (A1) (Sabar et al., 2015).

$$Index = \arg\max\left(q_i(t) + c \cdot \sqrt{\frac{2\log \sum_{j=LLH_1}^{LLH_n} n_j(t)}{n_i(t)}} \right) \tag{A1}$$

Where, c is a scaling factor which controls the trade-off of the heuristics that has the best reward and the one that has been frequently applied. LLH_n is the number of heuristics. The parameter $q_i(t)$ is the empirical reward and $n_i(t)$ is the number of times that i^{th} heuristic (LLH_i)that has been used.

- **Step 5:** *Select one from LLHs.* According to the selection index calculated from step 4, the corresponding heuristics is selected. Eight heuristics (denoted as LLH1 to LLH 8) are used in this study::
  - LLH1: *one-point crossover*. LLH1 randomly selected one point, starting from beginning of individual to the point is copied from one parent, and the part from the point to the end is copied from the second parent. An example of one-point crossover is shown in **Figure A1**.
  - LLH2: *two-point crossover*. In LLH2, two points are randomly selected, starting from beginning of individual to the first point is copied from one parent, the part from first point to the second point is copied from the second parent, and the rest is copied from the first parent. An example of two-point crossover is shown in **FigureA2**.

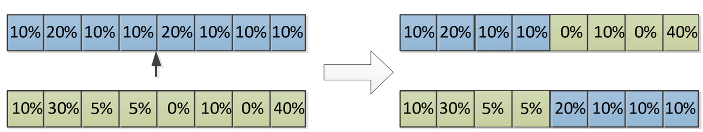


Figure A1 One-point crossover example

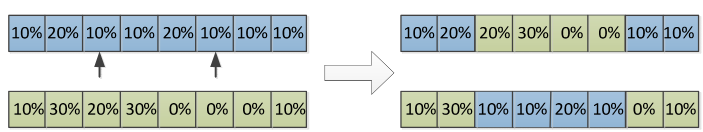


Figure A2 Two-point crossover example

  - LLH3: *arithmetic crossover*. LLH3 works by taking the weighted average of the two parents: one parent is the best individual and the other parent is randomly selected, as shown in Equation(A2)

$$x_{new}(j) = \alpha \cdot x_{best}(j) + (1-\alpha) \cdot x_r(j) \tag{A2}$$

Where, $x_{new}(j)$ is the new element in the new individual and $x_r(j)$ is the *j th* element in the randomly selected individual, $x_{best}(j)$ is the j th element of the best individual, and α is the weight.

- LLH4: *random mutation*. The random mutation randomly selects one or several points from a given solution and changes their values in the search range. An example of random mutation is shown in **Figure A3**.

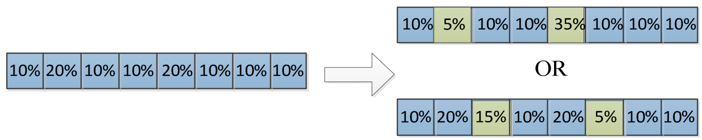


Figure A3 Random mutation example

- LLH5: *differential mutation 1*. LLH5 randomly selects three individuals and then use them to generate a new individual using Equation (A3).

$$x_{new}(j) = x_{r1}(j) + \alpha \cdot [x_{r2}(j) - x_{r3}(j)] \quad (A3)$$

  Where, $x_{new}(j)$ is the *j th* new element in the *new* individual, $x_{r1}(j)$, $x_{r2}(j)$ and $x_{r3}(j)$ are the j th element of the three randomly selected individuals, and α is the mutation parameter.
- LLH6: *differential mutation 2*. In LLH6, we first randomly selects two individuals and then use the best individual to generate the new one using Equation (A4).

$$x_{new}(j) = x_{best}(j) + \alpha \cdot [x_{r1}(j) - x_{r2}(j)] \quad (A4)$$

- LLH7: *differential mutation 3*. It randomly selects three individuals and use the best individual to generate a new one using Equation (A5)

$$x_{new}(j) = x_{r1}(j) + \alpha \cdot [x_{r2}(j) - x_{r3}(j)] + \beta \cdot [x_{best}(j) - x_{r1}(j)] \quad (A5)$$

  Where, α and β are the mutation parameters.
- LLH8: *parameterized Gaussian mutation.* LLH8 uses the best individual to generate new individual with Gaussian mutation as shown in Equation (A6).

$$x_{new}(j) = x_{best}(j) + gauss(\mu, \sigma) \quad (A6)$$

  Where, $gauss(\mu,\sigma)$ can generate one gauss distributed value with mean μ and standard deviation σ.

- **Step 6:** *Deal with constraints.* The new generated individual may violate the problem constraints in Equations (2) and(3). If the constraints are violated, we use Equations (A7)-(A9) to return it into a feasible solution.

$$x(j) = 0, \text{ if } x(j) < 0 \quad (A7)$$

$$x(j) = 1, \text{ if } x(j) > 1 \quad (A8)$$

$$x(j) = \frac{x(j)}{\sum_j x(j)} \quad (A9)$$

- **Step 7**: *Calculate fitness*. This step calculates the fitness of the new individual using Equation (1).
- **Step 8:** *Update information of LLH.* This step updates the performance impact of each LLH. It is updated based on the quality of the new generated individual. The quality is updated using Equations (A10)and(A11) and application frequency of each LLH is updated using Equation (A12).

$$q_i(t+1) = q_i(t) + \Delta, \text{ if the fitness of new individual is better.} \quad (A10)$$

$$q_i(t+1) = \max\{q_i(t) - \Delta, 0\}, \text{ if the fitness of new individual is worse.} \quad (A11)$$

$$n_i(t+1) = n_i(t) + 1 \quad \text{(A12)}$$

Where, Δ is the absolute difference between the objective function value of the new individual and that of the old best individual, and other parameters' meaning is the same with Equation (A1).

- **Step 9:** *Stopping condition.* It determines when the hyper-heuristic method will stop. It checks the maximum number of iterations and if it has been reached, the search will stop and return the best solution. Otherwise, it goes to step 10.
- **Step 10:** *Update population.* If the fitness of the new individual is better than the worst one in the population, the old one will be replace with the new one. Then, go to step 4.

References

Bertini, R.L., Leal, M.T., 2005. Empirical study of traffic features at a freeway lane drop. Journal of Transportation Engineering, 131(6), 397-407.

Chamberlayne, E., Rakha, H., Bish, D., 2012. Modeling the capacity drop phenomenon at freeway bottlenecks using the INTEGRATION software. Transportation Letters-The International Journal of Transportation Research, 4(4), 227-242.

Chen, D., Ahn, S., 2015. Variable speed limit control for severe non-recurrent freeway bottlenecks. Transportation Research Part C: Emerging Technologies, 51, 210-230.

Chen, D., Ahn, S., Hegyi, A., 2014. Variable speed limit control for steady and oscillatory queues at fixed freeway bottlenecks. Transportation Research Part B: Methodological, 70, 340-358.

Fukushima, M., 2011. The latest trend of v2x driver assistance systems in Japan. Computer Networks, 55(14), 3134-3141.

Gong, S., Du, L., 2016. Optimal location of advance warning for mandatory lane change near a two-lane highway off-ramp. Transportation Research Part B Methodological, 84, 1-30.

Hadiuzzaman, M., Qiu, T.Z., 2013. Cell transmission model based variable speed limit control for freeways. Canadian Journal of Civil Engineering, 40(1), 46-56.

Hadiuzzaman, M., Qiu, T.Z., Lu, X.Y., 2013. Variable speed limit control design for relieving congestion caused by active bottlenecks. Journal of Transportation Engineering, 139(4), 358-370.

Hayat, M.T., Park, H., Smith, B.L., 2016. Investigating driver response time to freeway merge advisories in a connected vehicle environment. Transportation Research Record: Journal of the Transportation Research Board, No. 2559, pp. 131–140.

Hyper-heuristic, 2017 https://en.wikipedia.org/wiki/Hyper-heuristic [Online; accessed June 13, 2017].

Jin, W.L., 2010. A kinematic wave theory of lane-changing traffic flow. Transportation Research Part B: Methodological, 44(8), 1001-1021.

Jin, W.L., Jin, H., 2014. Analysis and design of a variable speed limit control system at a freeway lane-drop bottleneck: A switched systems approach. In: 2014 IEEE 53rd Annual Conference on Decision and Control (CDC), IEEE, pp. 1753-1758.

Jin, H.Y., Jin, W.L., 2015. Control of a lane-drop bottleneck through variable speed limits. Transportation Research Part C: Emerging Technologies, 58, 568-584.

Kanazawa, F., Kanoshima, H., Sakai, K., Suzuki, K., 2010. Field operational tests of Smartway in Japan. IATSS Research, 34(1), 31-34.

Laval, J.A., Daganzo, C.F., 2006. Lane-changing in traffic streams. Transportation Research Part B: Methodological, 40(3), 251-264.

Mai, T., Jiang, R., Chung, E., 2016. A Cooperative Intelligent Transport Systems (C-ITS)-based lane-changing advisory for weaving sections. Journal of Advanced Transportation, 50(5), 752-768.

Sabar, N.R., Zhang, X.J., Song, A., 2015. A math-hyper-heuristic approach for large-scale vehicle routing problems with time windows. In: 2015 IEEE Congress on Evolutionary Computation (CEC), IEEE, pp. 830-837.

Schakel, W.J., Arem, B.V., 2014. Improving traffic flow efficiency by in-car advice on lane, speed, and headway. IEEE Transactions on Intelligent Transportation Systems, 15(4), 1597-1606.

Srivastava, A., Jin, W., 2016. A lane changing cell transmission model for modelling capacity drop at lane drop bottlenecks. In: 2016 the 95th Transportation Research Board Annual Meeting, No. 16-5452.

Transport for NSW, 2015. Cooperative Intelligent Transport Systems. URL: http://roadsafety.transport.nsw.gov.au/research/roadsafetytechnology/cits/cits-signal.jpg. [Online; accessed March 27, 2017].

Yuan, K., Knoop, V.L., Hoogendoorn, S.P., 2017. A microscopic investigation into the capacity drop: impacts of longitudinal behavior on the queue discharge rate. Transportation Science, Doi: https://doi.org/10.1287/trsc.2017.0745

Zhang, Y., Ioannou, P.A., 2015. Combined variable speed limit and lane change control for truck-dominant highway segment. In: 2015 IEEE 18th International Conference on Intelligent Transportation Systems (ITSC), IEEE, pp. 1163-1168.

Zhang, Y., Ioannou, P.A., 2017. Combined variable speed limit and lane change control for highway traffic. IEEE Transactions on Intelligent Transportation Systems. 18(7), 1812-1823.