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A C-ITS-based lane-changing advisory for weaving sections Q1

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SUMMARY

Weaving sections, a common design of motorways, require extensive lane-change manoeuvres. Numerous studies have found that drivers tend to make their lane changes as soon as they enter the weaving section, as the traffic volume increases. Congestion builds up as a result of this high lane-changing concentration. Importantly, such congestion also limits the use of existing infrastructure, the weaving section downstream. This behaviour thus affects both safety and operational aspects. The potential tool for managing motorways effectively and efficiently is cooperative intelligent transport systems (C-ITS). This research investigates a lane-change distribution advisory application based on C-ITS for weaving vehicles in weaving sections.

The objective of this research is to alleviate the lane-changing concentration problem by coordinating weaving vehicles to ensure that such lane-changing activities are evenly distributed over the existing weaving length. This is achieved by sending individual messages to drivers based on their location to advise them when to start their lane change.

The research applied a microscopic simulation in AIMSUN to evaluate the proposed strategy's effectiveness in a one-sided ramp weave. The proposed strategy was evaluated using different weaving advisory proportions, traffic demands and penetration rates. The evaluation revealed that the proposed lane-changing advisory has the potential to significantly improve delay. Copyright © 2016 John Wiley & Sons, Ltd.

KEY WORDS: cooperative intelligent transport systems (C-ITS); weaving section; lane-change distribution; lane-change advisory Q3

1. INTRODUCTION

Weaving sections, a common design of motorways, are defined as the crossing of two or more traffic streams travelling in the same direction along a significant length of motorway without the aid of traffic control devices [1]. A characteristic of such sections is that they require extensive lane-change manoeuvres [2]. A lane change is a process involving a high level of interaction when vehicles manoeuvre laterally from one lane to another [3]. These interactions are difficult to predict as vehicles have to negotiate with their surrounding counterparts to perform lane changes [4]. Jula *et al.* [5] affirmed that lane-changing manoeuvres are one of the riskiest manoeuvres that drivers have to perform in a motorway system to merge or diverge into the destination lane. Even though the lane-change crash problem is relatively small compared with other types of crashes (in the USA, lane-changings crashes account for only 4% of all police-reported crashes and around 0.5% of all fatalities), it is responsible for one-tenth of all traffic delays caused by crashes [2].

Weaving sections are also the main source of traffic bottleneck congestion [6], which can reduce traffic efficiency by 20% to 50% [7]. The bottleneck problem in weaving sections is the result of the concentration of merging and diverging manoeuvers [8–12]. Empirical data have shown that drivers tend to perform lane changes close to the merge gore as the traffic volume increases, and this behaviour builds up congestion. Hence, weaving manoeuvres affect driving comfort, safety and operational aspects.

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Thanks to advancements in wireless technology, vehicles are now able to exchange information with other vehicles and infrastructures. This emerging technology, the so-called C-ITS, offers a new way to increase traffic safety, productivity and efficiency [13]. The main distinct characteristic of C-ITS is the ability to guide and/or control individual or targeted groups of different vehicles.

This paper seeks a possible way to manage weaving sections using C-ITS for having better lane-changing distribution. Specifically, it presents a strategy to tackle the lane concentration problem for a one-sided ramp-weave by guiding weaving vehicles to execute lane changes at specific reference points.

The paper is structured as follows. Section 2 presents the literature review, which includes discussion of the lane-changing concentration in weaving sections and how C-ITS can assist to alleviate the problem. Section 3 describes the proposed strategy within the study. Section 4 outlines the simulation test, which includes the simulation settings and the result analyses, before the conclusion in Section 5.

2. LITERATURE REVIEW ON LANE-CHANGING CONCENTRATION

This section reviews the related literature on the lane-changing problem in weaving sections. It then provides information regarding how C-ITS helps to alleviate the problem, which forms the foundation for the study.

When reviewing driving behaviour studies in the literature [8–12], one can see that drivers are more likely to change lane as close to the merge gore as possible when they enter weaving sections.

Cassidy *et al.* [8] were among the first to investigate this behaviour. Their research concluded that a very high concentration of flow and a high rate of lane-changing manoeuvres occurred near the merge gore. To be more specific, they found that the majority of lane changes were made in the first 73 m of a 445 m weaving section. The same behaviour was found even where the weaving length was relatively long. This behaviour tends to increase when the flow rate increases because drivers become more anxious to change lanes over a shorter travel distance, and this increased flow rate encourages them to perform lane changes as soon as possible. The ‘critical region’ occurs where congestion starts to build up and to propagate upstream.

Kwon *et al.* [9] studied weaving behaviour by investigating its characteristics at a 129 m one-sided weaving section. The video analysis demonstrated that most of the lane changes took place in the first half (65 m) of the weaving section. When the weaving flow increases, diverging vehicles locate themselves into the auxiliary lane right after they approach the weaving section. Merging vehicles first enter the auxiliary lane, and then travel a considerable distance before changing lane to the mainstream. Congestion is created right after the merge gore, which reduces weaving capacity dramatically.

Denny and Williams [10] examined the capacity and quality of service of several weaving sections in California. Their 2 h of video data proved that weaving vehicles tried to execute lane changes as soon as they could in the weaving area. This shows that the weaving capacity is mostly associated with the merging gore areas. It was found that approximately 85% of the manoeuvres took place in the first 120 to 150 m of the 400 m weaving sections. As a result, a queue formed near the merge gore, while the weaving section downstream was starved for demand.

Another study was conducted by Ho Lee [11] to investigate the bottleneck at weaving sections. One important observation emerging from this research was that the tendency of diverging vehicles to change lane close to merge gore areas was influenced by the space availability in the auxiliary lane. In fact, diverging vehicles are more likely to change lanes close to the merge gore if the ramp to freeway traffic is low. When the number of diverging vehicles that change lanes close to the merge gore increases, the bottleneck becomes more severe.

The latest empirical data were investigated by Al-Jameel [12]. Within that research, the author divided the 400 m weaving section into four segments from the merge gore (0–50, 50–100, 100–150 and >150 m) and explored the lane-changing location. The research found that approximately 80% of merging vehicles and up to 90% of diverging vehicles completed lane changes in the first 100 m of the 400 m weaving section.

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All of the aforementioned studies point out that drivers are more likely to perform lane changes as soon as they enter the weaving sections, especially when the traffic flow is increasing. This behaviour creates a very high lane-changing concentration, up to 90%. Thus, congestion builds up, limiting weaving capacity.

The next question is whether C-ITS can contribute to alleviating high lane-changing concentration. From a driving psychology point of view, moving to the destination lane so as not to miss the entrance/exit is a common perspective for drivers approaching weaving sections. The anxiety of missing the entrance/exit point intensifies as the traffic flow increases. Consequently, drivers are not willing to coordinate with each other, therefore causing a high-concentration phenomenon.

Cooperative intelligent transport systems can collect a vehicle's origin and destination (OD) information at an individual base and provide personalized messages back to individual vehicles [13]. With the individuals' OD information, weaving vehicles (i.e. those vehicles that have to perform lane changes to merge or diverge in weaving sections) and non-weaving vehicles can be distinguished, and their lane-changing choices (i.e. when and where to start lane changing) can be affected and coordinated by feeding different messages/advisory to different individual vehicles.

In summary, C-ITS has the potential to coordinate lane-changing choices among weaving vehicles. In this way, the lane-changing concentration problem can be alleviated, and the entire weaving section can be fully utilized.

3. C-ITS-BASED LANE CHANGE DISTRIBUTION FOR WEAVING SECTION STRATEGY

As analysed in Section 2, a very high number of lane-change manoeuvres occurs close to the merge gore area, especially when the traffic flow is close to capacity (Figure 1b) (note that this is the left-side **F1** driving system). This means the entire length of the weaving section is not fully utilized, which is why the length of the weaving zone has no effect on the capacity of the weaving section beyond a particular value [14]. Hence, the objective of the proposed strategy is to distribute weaving vehicles evenly over the existing infrastructure by guiding them to a reference point at which they can start to merge or diverge. Spreading out the merging and diverging proportion is expected to reduce the lane-changing concentration and to improve traffic conditions at weaving sections (Figure 1c).

Weaving sections are classified into two different types, one-sided and two-sided, based on their configurations and the minimum number of lane changings required. For two reasons, our methodology focuses only on one-sided weaving section, in which no weaving manoeuvres require more than two lane changes to be completed successfully and all the weaving movement are taken on one side of the section. Firstly, most weaving sections are one sided [1]. Secondly, unlike one-sided weaving sections, there are limited data and literature on the lane flow distribution and lane changing behavior at two-sided weaving sections. Hence, in this study, the proposed methodology is limited to the one-sided weaving section only.

The example network used in this study is from Al-Jameel's paper [12], and the geometry is demonstrated in Figure 1a. The main reason for choosing this weaving section was that the literature [12] provided detailed field data regarding the number of lane changes (NL) with location information, which was extracted from the video record. Without this information, it would have been difficult to model, calibrate and validate the high lane-changing concentration in the micro-simulation.

The selected weaving section was part of the M60 Motorway, Manchester City, UK, and the weaving length was 400 m, as shown in Figure 2. The flow of the weaving section was from 4200 to **F2** 7260 veh/h. The bottleneck occurs when the total flow was at approximately 7100 veh/h and total weaving flow was at 1900 veh/h. As can be seen from Figure 1a, the weaving section was divided into four different small segments. The amount of lane-changes data extracted from a 4-h video was presented based on these segments. In addition, these segments were used as reference points for certain weaving vehicles to start gap-finding and performing lane changes. Therefore, there were four groups for the selected weaving section.

Figure 3 shows the flow chart of the proposed lane-changing advisory strategy. **F3**

The first step is to collect OD information through a vehicle-to-infrastructure communication link. Assuming a road-side unit (RSU) located 1000 m upstream of the weaving section, all vehicles with

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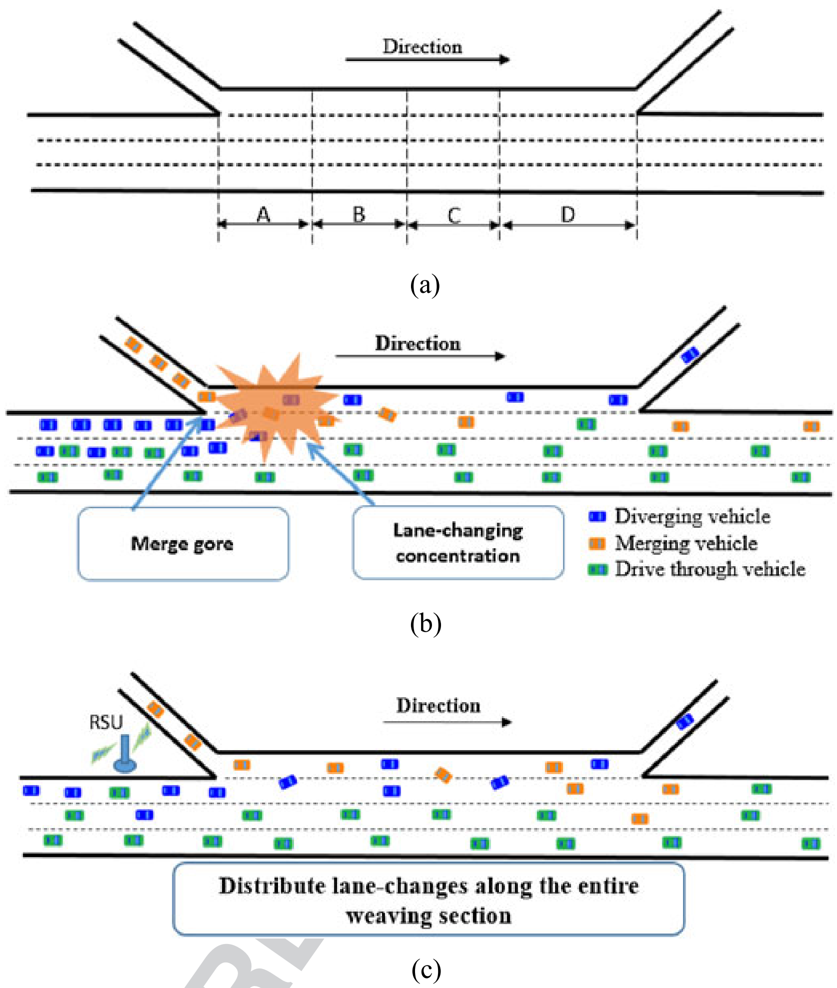

Figure 1. Lane-changing advisory application strategy: (a) weaving section geometry, (b) weaving section without the strategy and (c) weaving section with the advisory application.

Q4

Figure 2. Aerial map of the weaving section.

C-ITS capability would send their OD information to the RSU. In the second step, vehicles are identified as weaving or non-weaving vehicles. For non-weaving vehicles, no further actions are required, and they will drive through the weaving section as usual. For weaving vehicles, the strategy further groups them and provides lane-changing advisory accordingly.

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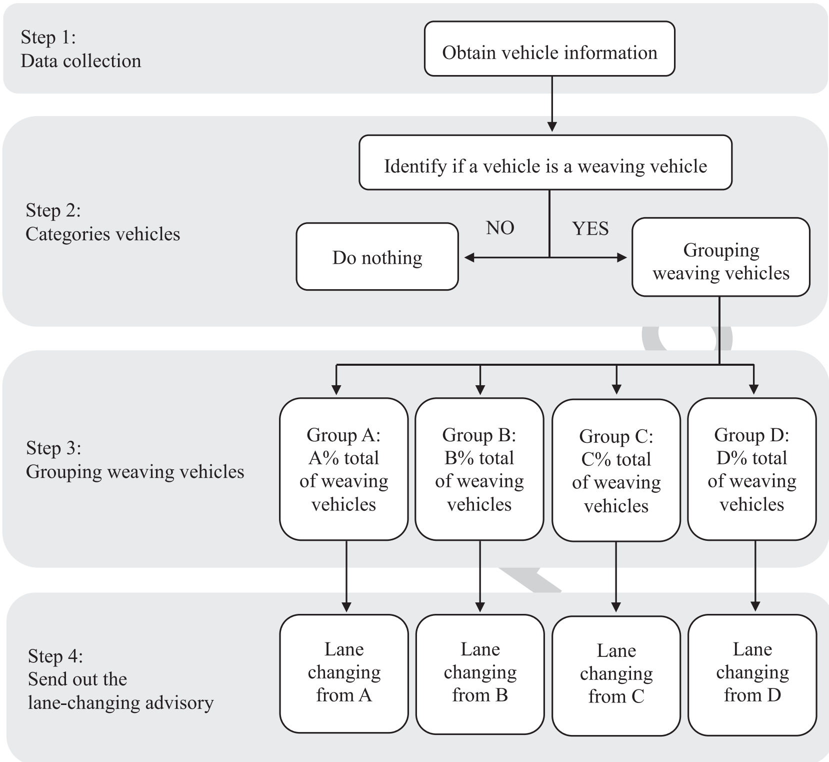

Figure 3. Flow-chart of the lane-changing advisory application.

Step 3 is to put a weaving vehicle into one of the four groups. Once an identified weaving vehicle enters, a random number from 0.0 to 1.0 is generated and assigned to the vehicle for the grouping. The generated random number follows uniform distribution to guarantee the grouping is user equal. For example, if the expected percentages for the four groups are 30%, 15%, 15% and 40%, the ranges of the random number for the four groups are shown in Table I. If the random number falls between **T1** 0.0 and 0.3, the vehicle is assigned into Group A (Table I).

After the grouping, Step 4 is to send out the lane-changing advisory to each vehicle to indicate where they can start executing a lane change. For example, vehicles in Group A can start to change lane when they enter the weaving section and find a proper gap. Group B should not manoeuvre to another lane until they reach the second segment (segment B) in the weaving section. Group C should change lane starting from the third segment (segment C) in the section. Finally, group D can change lane when reaching segment D.

The weaving vehicles will receive the in-vehicle messages in the form of sound and text, as is currently implemented in many C-ITS applications around the globe, such as in Japan [15, 16]. Two different messages are as follows:

- ‘Distance to change lane’ (distance countdown to the reference location);
- ‘Please start looking for a gap and perform your lane change’: this message is forwarded to weaving vehicles when they reach the reference point in the weaving section to inform drivers that they can start to change lane.

Table I. Grouping example.

Group	Range
Group A	(0.0, 0.3)
Group B	(0.3, 0.45)
Group C	(0.45, 0.6)
Group D	(0.6, 1.0)

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Table II. Default and calibrated values in AIMSUN.

Road types	Motorway		On/off ramp	
Parameter	Default value	Calibrated value	Default value	Calibrated value
Distance to zone 1 (m)	500	650	300	300
Distance to zone 2 (m)	100	450	40	120

4. SIMULATION TEST AND RESULT ANALYSIS

This section first outlines the test bed. It then describes the simulation steps undertaken when applying the strategy in the weaving section. Finally, it comprehensively tests the strategy using different scenarios.

4.1. TEST BED

The tests were evaluated using the commercially available microscopic traffic simulation software, AIMSUN. This powerful microscopic traffic simulation software can build the model easily, with errors kept to a minimum [17]. AIMSUN also offers the API function, which enables an interface with external applications so that users can apply the proposed strategy within the study. The version used in this study is 8.0.4. Q5

The selected weaving section, from the M60 Motorway, Manchester City, UK, had serious congestion during peak hours [12]. The weaving length was 400 m. The network was modelled in AIMSUN with a 1-h simulation period (the peak hour) and a 15-min warm-up. To ensure the test's credibility, each of the tests was run with 20 different replications. The results were drawn by taking the average of 20 replications to diminish the outcome variations.

It is not easy to record and capture weaving behaviour in the weaving section. The main difficulty is obtaining the actual NL in the weaving section. Therefore, the demand data for the 400 m one-sided ramp weave were taken from Al-Jameel's paper [12]. The model had the following traffic flow rates†:

- Freeway to freeway (FF): 5300 veh/h;
- Freeway to ramp (FR): 900 veh/h;
- Ramp to freeway (RF): 900 veh/h;
- Ramp to ramp (RR): 100 veh/h.

Calibration is the next key step in modelling the test bed. This interactive process consists of changing model parameters and comparing model outputs with a set of real data in order to reflect the observed local traffic and driving behaviour conditions being modelled [18]. As analysed in Section 2, the major problem for weaving sections is the high lane-changing concentration. The primary objective of the model calibration is to represent the lane-changing phenomenon in the simulation model. Therefore, the data set used for calibration was the NL in the weaving section from Al-Jameel [12].

Al-Jameel [12] investigated NL in terms of percentage in the weaving section by using video to capture the behaviour. With the 400 m weaving section, the author divided the weaving section into four different segments, namely, A (50 m), B (50 m), C (50 m) and D (250 m), and recorded the NL (of the weaving vehicles) in each segment.

The model represented the lane-changing concentration problem by adjusting the 'distance to zone' parameters in AIMSUN. The default and calibrated values are shown in Table II. Other parameters, such as lane-changing cooperation and side-lane merging distance, were also adjusted. However, no significant difference was observed. **T2**

The NL percentage of the observed values from Al-Jameel [12] and the values before and after calibration are revealed in Table III. The results demonstrated that the calibrated values were close to the observed values. This was also the best attempt achieved among numerous simulation runs. **T3**

†The traffic composition considers cars only; other vehicle types (such as trucks) are not included.

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Table III. Calibration results.

	Merging vehicles (%)				Diverging vehicles (%)			
Segment	A	B	C	D	A	B	C	D
Observed value	45	38	12	5	54	43	3	0
Default parameter	25	27	13	35	36	21	11	31
Calibrated parameter	40	50	9	1	54	37	7	2

Another data set from the same weaving section for the different day [19] was used to validate the model. The validation results are shown in Table IV. T4

The validation results indicate that there was an agreement between the observed and the simulated values for merging vehicles. It was also found that the simulated value of diverging vehicles in zone A was 16% lower than that of observed value. However, Al-Jameel [12] stated that the location of the bottleneck occurred in the weaving section is about 70 m downstream from the merge gore area. Accordingly, it is reasonable to compare the sum of the first 100 m.

The total NL of the observed values in segments A and B (100 m from the merge fore) for merging and diverging vehicles are 86% and 90%, respectively, while that of the modelled results were 86% and 84%, proportionally. These validation results clearly demonstrate that the model is well calibrated.

The test bed, the M60 Motorway (Manchester City, UK) was now ready for comprehensive results analysis.

4.2. Simulation settings

4.2.1. Performance indicator

Choosing appropriate indicators to evaluate the weaving section is vital [20]. Previous research has often viewed the average speed as one of the operational indicators. However, Cassidy and May [20] found that average vehicle speed did not always reflect the section operation. When the relationship between the speed and volume/capacity was plotted, it was observed that the speed was insensitive to the high flow [8]. This was further explained by Denny and Williams [10], who stated that because of the bottleneck ftabormation, speed would be lowest close to the merge gore areas Q6 where the maximum interaction between merging and diverging vehicles occurred. The speed would increase once they moved through the bottleneck location. Hence, average speed was not used as an operational performance indicator in this study. Instead, speed over the entire weaving section shows how smooth drivers crossed the weaving section and examines whether the concentration of lane-changing problem has been alleviated successfully. This can be achieved by putting dense detectors over the entire weaving section. In this study, lane-by-lane detectors were put across the entire weaving section, at an average distance of 10-m. This study used 1-min aggregation for all detector measures. The recorded speed over the weaving section can be used to either calculate the time-mean speed over space or plot speed contours.

For the operational indicator, this study adopted average delay, calculated as the difference between the actual travel time and the free-flow travel time. Actual travel time was recorded by API, which collected the travel time of individual vehicles passing the network and then calculated the average delay. The free-flow travel times of the mainline vehicles (FF and FR) and of the on-ramp vehicles (FR and RR) were calculated to be speeds of 100 and 80 km/h, respectively. For mainline vehicles, the actual travel time was calculated from 500 m upstream from the merge gore to downstream where

Table IV. Validation results.

	Merging vehicles (%)				Diverging vehicles (%)			
Segment	A	B	C	D	A	B	C	D
Observed value	55	31	14	0	67	23	10	0
Simulated parameter	46	40	13	1	51	33	10	6

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vehicles passed the weaving section, while this number for on-ramp vehicles was recorded as 130 m from the merge gore to the weaving section downstream. The unit of average delay time was second per vehicle (s/veh).

Another operational indicator was the actual saving time, the difference of the average delay between test scenarios (base case and control case). The unit of actual saving time was second per vehicle (s/veh).

In short, the following indicators were adopted within the study:

- To understand how smooth drivers crossed the weaving section

- Time-mean speed over the weaving section
- Speed contour

- Operational indicator

- Average delay (sec/veh) or actual saving time (sec/veh)

4.2.2. API development

Before presenting the development of the API code, the following assumptions were made:

- The communication signal strength was 100% guaranteed; the so-called wireless access in vehicular environment standard, composed by IEEE 802.11p and IEEE 1690.x, is assumed to be provided;
- Every vehicle followed the guidance given by the infrastructure;
- Every vehicle within the communication zone would be tracked by RSU so their destination lanes were identified.

The proposed strategy was implemented using the API functions provided by AIMSUN. Applying the lane changing in the right way is important for the credibility of the simulation evaluation. According to Section 3, the proposed strategy only provides advice to certain vehicles regarding where they should start to perform their lane changing but does not force any vehicles to change lane. In the developed API code, all lane changings are still governed by the lane-changing model embedded in AIMSUN. The developed API code provides only a reference point for C-ITS-enabled vehicles to undertake lane changing.

4.2.3. Test scenarios

A comprehensive evaluation of the proposed strategy is conducted in this sub-section, including tests for distribution percentages, for different demand settings and for different penetration rates. In the first test for distribution percentages and different demand settings, the penetration rate is assumed to be 100%.

Two test scenarios were examined to demonstrate the effectiveness of the proposed strategy:

- Base case: the case without applying the strategy in which the bottleneck occurred;
- Control case: the lane-changing advisory applied for weaving vehicles.

4.3. Result analyses

4.3.1. Tests for distribution percentage

In this study, the focus was to investigate the feasibility and effectiveness of the lane-changing application. Hence, no sophisticated optimization technique was involved to seek the optimal solution of the distribution percentage. Three combinations of the distribution percentage were tested. Table V lists the three tested combinations. **T5**

Table V. Three tested combinations of the distribution percentage.

Segment	A (50 m)	B (50 m)	C (50 m)	D (250 m)
Combination 1 (%)	30	15	15	40
Combination 2 (%)	25	25	25	25
Combination 3 (%)	18	18	18	46

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The first combination is the initial test. In the second combination, 25% of total weaving vehicles were advised to change lane at the start of each of the weaving segments. The aim of Combination 2 is to examine how the network performs if an equal weaving proportion was advised for each of the segments. Note that the lengths of the segments are not equal.

As segment D accounts for more than 60% of the weaving section length (250 m over 400 m), nearly half of the total weaving vehicles (46%) are advised to go to segment D in Combination 3.

Finally, we would like to advise equal weaving proportions changing lane in the first 150 m.

Taking Combination 1 as an example, the 400 m weaving section is divided into four different small segments, namely, A, B, C and D. A proportion of weaving vehicles is then assigned; this assigned weaving advisory proportion of vehicles should change to another lane only when reaching a reference segment such as

- 30% of weaving vehicles are able to start the manoeuvres from segment A in the weaving section (merge gore), which means they can either merge or diverge in segment A, B, C or D as long as gaps are available.
- Another 15% of weaving vehicles should not manoeuvre to another lane until they reach segment B (50 m from merge gore).
- Similarly, 15% of weaving vehicles are encouraged to change lane when approaching segment C in the weaving section (100 m from merge gore).
- Finally, 40% of total weaving vehicles should perform a lane change in segment D only (150 m from merge gore).

The time-mean speed over the auxiliary lane and lane 3 are shown in Figures 4 and 5, respectively. **F4 F5** The reason for choosing these two lanes was that they experience most of the lane changes in the weaving section. Accordingly, this study also used the speed data from these two lanes to illustrate speed contour.

As can be seen from Figures 4 and 5, the proposed strategy can smooth the speed over the entire weaving section. Compared with the base case, the speed curves over space (either auxiliary lane in Figure 4 or lane 3 in Figure 5) in the control cases were much flatter, and the obvious speed drop near the merge gore no longer existed. This indicates the lane-changing concentration problem was alleviated by the strategy.

When comparing the three combinations, the green curves in both figures show slightly smoother speed distribution over space, which is the objective of the lane-changing advisory. Hence, among these three combinations, Combination 3 slighly outperforms the other two combinations (in terms of bottleneck alleviation).

The speed contours of the auxiliary lane and lane 3 are illustrated in Figures 6 and 7 (the speed **F6 F7** contours are samples but all of the replications produced similar patterns). From the two figures, a similar phenomenon with time-mean speed curve comparison can be found. Firstly, the figures show

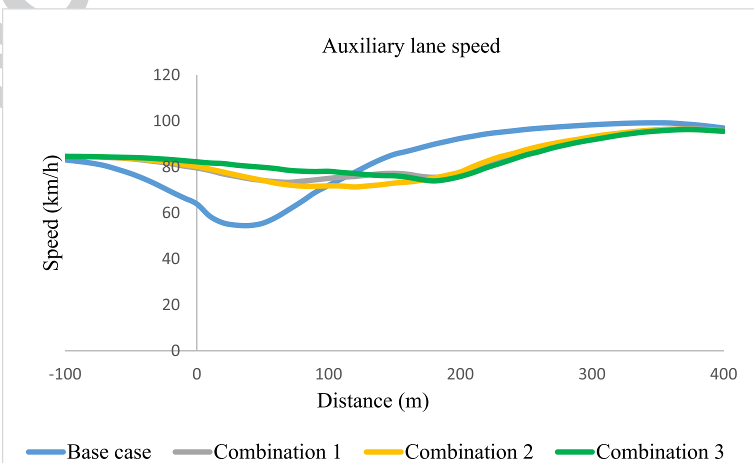

Figure 4. Time mean speed over auxiliary lane.

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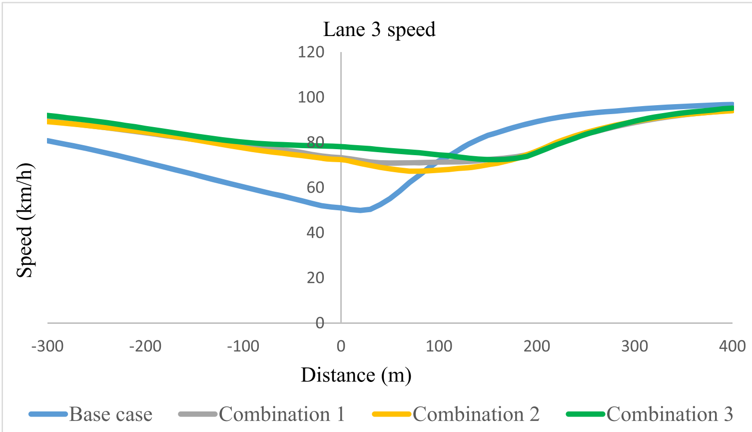

Figure 5. Time mean speed over lane 3.

that the proposed strategy can easily handle the lane-changing concentration problem. Secondly, Combination 3 shows a slightly better performance over the other two combinations.

In Table VI, the average delays from the base case and the three control cases are compared. It can clearly be seen that the average delay from the control cases was much lower than the corresponding figure of the base case. The differences of the three control cases were minor, especially between Combination 1 and Combination 3. Combination 2 had the best performance in the average delay, but Combination 3 had a smoother speed distribution over space that was the objective of the lane-changing advisory. Consequently, Combination 3 was selected as the optimal option of the three scenarios and used for the rest of the tests in this sub-section. **T6**

The *t*-test was also performed to examine whether the delay before and after the introduction of the C-ITS lane-changing advisory application was statistically significant. The null hypothesis was that there was no difference between the delay in the base case and the delay in the control cases. The test demonstrates the critical probability value (*p* value) at 5% significance level of four different movements in the weaving section. Because the *p* values of all movements were less than 0.05, the null hypothesis was rejected. In order words, the intervention of the C-ITS lane-changing advisory application significantly reduced the delay in the weaving section.

An analysis of the actual lane-changes distribution achieved by the proposed strategy was conducted for further investigation. Table VII lists the actual NL percentages before and after the activation of the strategy. **T7**

For merging vehicles, 8% of weaving vehicles, in the allowed 30% group, found a gap and changed lane in segment A. This means that another 22% of merging vehicles performed a lane change in segments B, C or D. Meanwhile, 26% and 21% of the merging vehicles moved to the mainstream in segment B and C, respectively. Finally, almost half of the merging vehicles (45%) executed a lane change in segment D (150 m from the merge gore).

Advising weaving vehicles to change lane at the last segments on the weaving section might increase the chance of missing the entrance/exit lane. Given that segment D comprises more than 60% length of the weaving section (250 over 400 m), weaving vehicles were able to change to destination lane within the provided length. AIMSUN provides a summary table where the number of miss (lost) vehicles can be checked. This summary table indicates that no vehicles missed the destination lane by following the advisory messages.

To reinforce the argument, for Combination 3, a minimum speed occurred at the position approximately 180 m from the merge gore (Figures 4 and 5). This indicates that most of the lane-changing activities completed at around this location.

The results further confirm that the proposed strategy could effectively distribute lane-change behaviour over the entire weaving section by providing the simple advisory.

4.3.2. Tests for different demand settings

This section analyses the impact of different OD matrices on the strategy. The OD test criteria selections were

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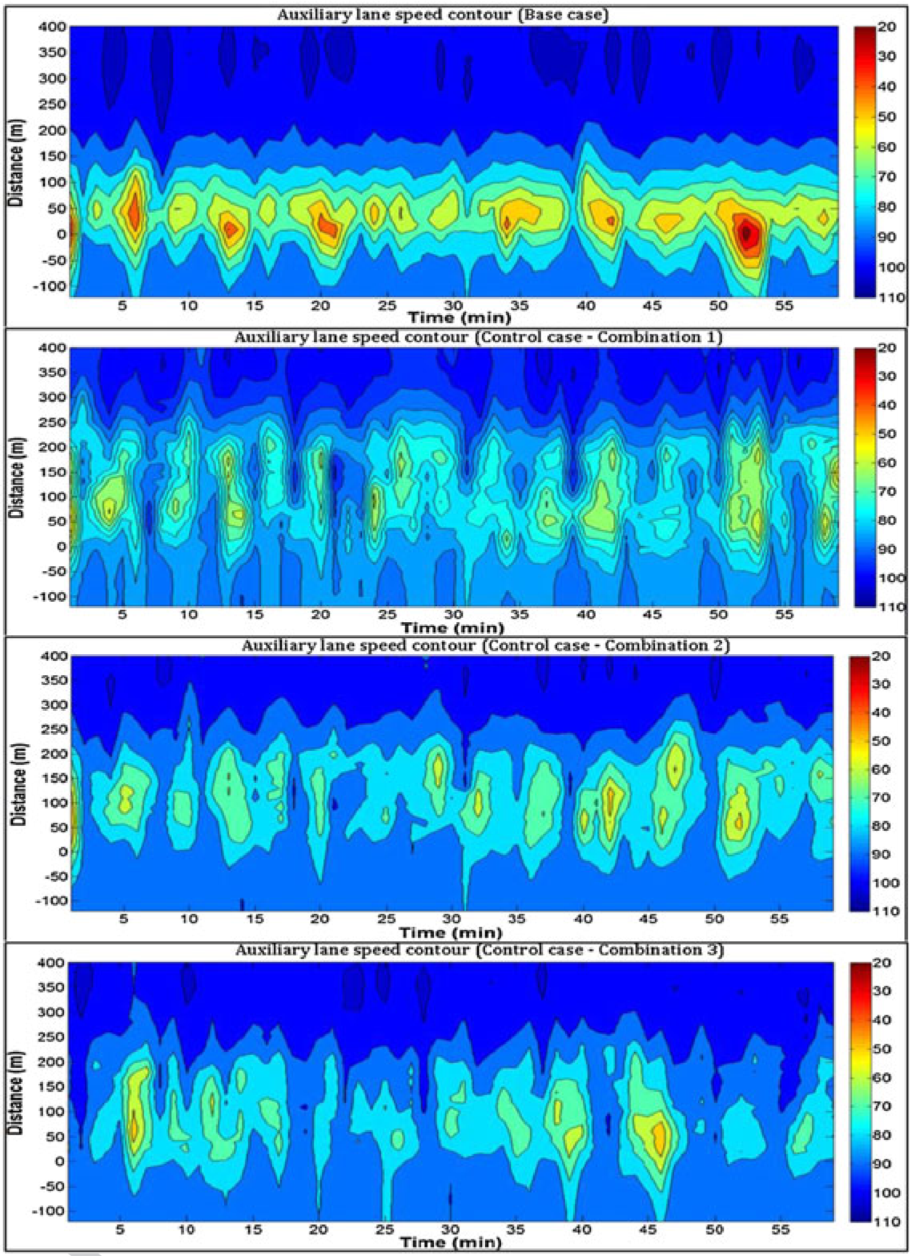

Figure 6. Contour speed of auxiliary lane.

- Maximum weaving flow of either RF or FR does not exceed 1260 vph.
- Maximum number of passenger cars in the weaving section is 2200 vph/lane.

The test was conducted using five different OD as shown in Table VIII. The five different tests **T8** resulted from a combination of one FF (5300 veh/h), one total weaving flow (1800 veh/h), one RR volume (100 veh/h) and five different RF ratios.[‡] The level of service (LOS) in each of the scenarios was E, which was analysed based on HCM 2010, chapter 12 [1]. LOS E indicated that the network was heavily congested. Note that the HCM 2010 does not distinguish LOS with different RF ratios.

The bar chart in Figure 8 compares the average delay between the base case and the control case, **F8** while the line graph shows the delay improvements in terms of percentage with the different ODs.

[‡]Ramp to freeway (RF) ratio: the ratio between ramp to freeway and the total weaving flow.

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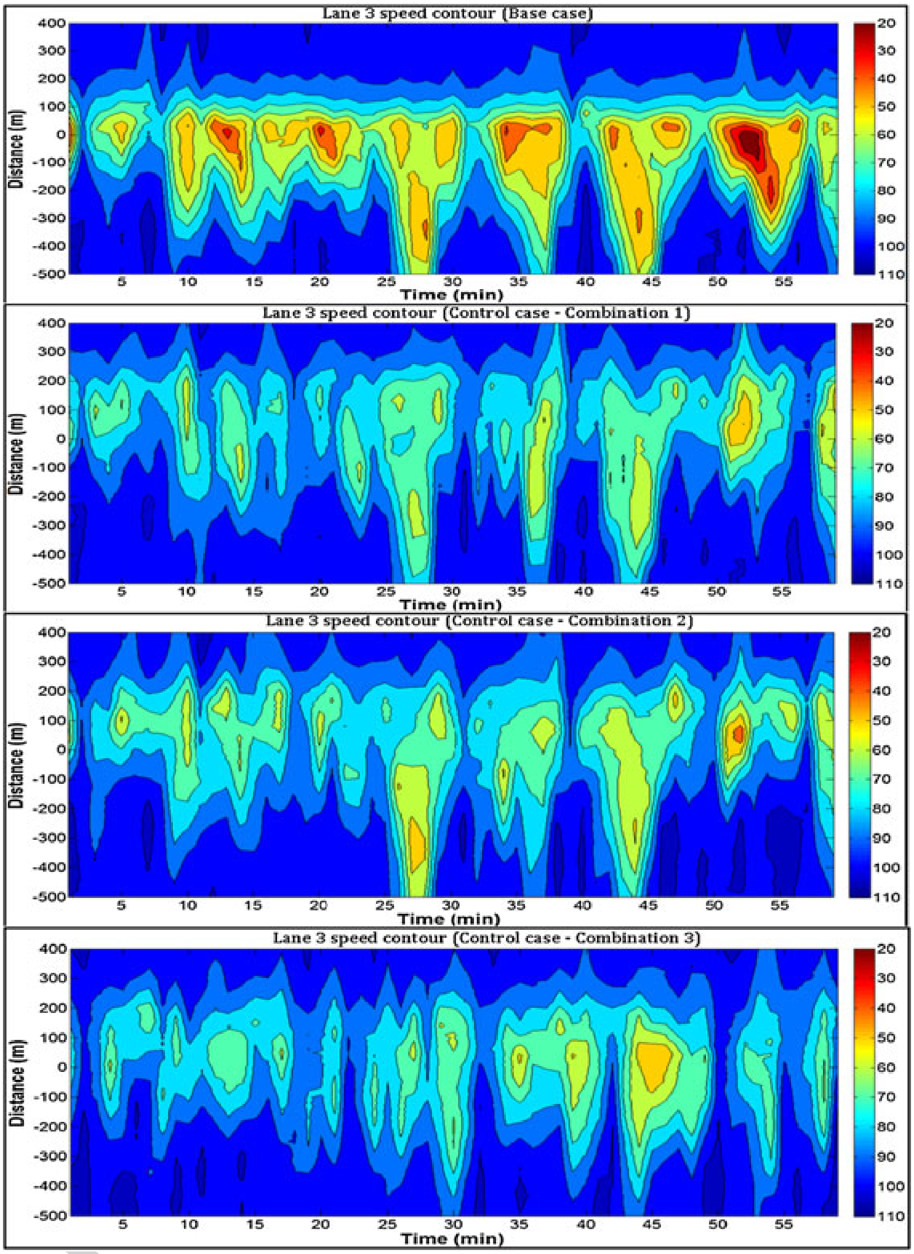

Figure 7. Contour speed of lane 3.

Table VI. Average delay comparison.

Movement	FF	FR	RF	RR	Average
Expected travel time (s/veh)	32.4	32.4	20.25	20.25	
Traffic volume (veh)	5300	900	900	100	
Delay in base case (s/veh)	8.86	13.29	5.72	3.74	8.95
Delay in control case (s/veh) Combination 1	5.33	8.25	4.49	3.08	5.55
Delay in control case (s/veh) Combination 2	5.41	8.43	4.69	2.94	5.66
Delay in control case (s/veh) Combination 3	5.31	8.45	4.67	3.05	5.58

FF, freeway to freeway; FR, freeway to ramp; RF, ramp to freeway; RR, ramp to ramp.

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Table VII. Actual number of lane-changes percentage.

	Merging vehicles (%)				Diverging vehicles (%)			
Segment	A	B	C	D	A	B	C	D
Base case	40	50	9	1	54	37	7	2
Control case	8	26	21	45	14	26	13	47

Table VIII. Different demand setting (veh/h).

Test	RF	FR	FF	Total weaving	RR	RF ratio
1	540	1260	5300	1800	100	0.3
2	720	1080				0.4
3	900	900				0.5
4	1080	720				0.6
5	1260	540				0.7

FF, freeway to freeway; FR, freeway to ramp; RF, ramp to freeway; RR, ramp to ramp.

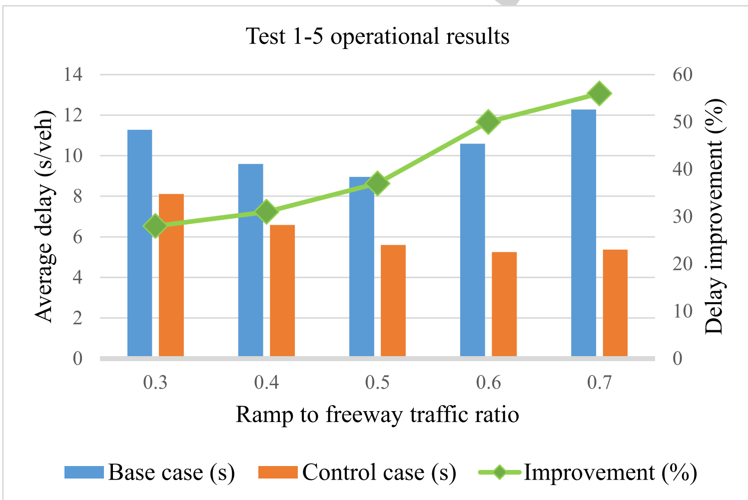

Figure 8. Results of tests for different demand settings.

The base case (blue column) shows that the weaving section had its minimum average delay when the RF ratio was at 0.5 with 8.95 (s/veh): that is, the two weaving flows (FR and RF) were equal. The delay value increased when either weaving flow (RF or FR) increased. This was because the one-sided ramp-weave required a single lane change; a more balanced weaving distribution of the total weaving flow results in a better gap utilization [21].

On the other hand, the average delay time in the control case (orange column) showed a different pattern. In fact, it reduced linearly as the RF ratio increased. The average delay of RF 0.3 in the control case was the highest, with more than 8 s. This number reduced gradually until the FR ratio was at 0.6 and 0.7.

To explain these results, the actual NL of weaving vehicles in different segments of the control case was recorded, as shown in Table IX. **T9**

The data in Table IX demonstrate that the lane-change concentration was spread further downstream of the weaving section when the RF ratio increased. This driving behavior was also explained and supported by Ho Lee [11], who stated that FR vehicles are more likely to diverge close to the merge gore area if the RF ratio is low. When the RF ratio increases, RF vehicles will change lane further downstream in the weaving section. As a result, the average delay time in the control case dropped as the RF ratio increased (i.e. highest at RF 0.3 and lowest at RF 0.7).

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Table IX. Actual NL in the weaving section with different RF ratios

Number of lane changes in the weaving section				
A	B	C	D	RF ratio
168	275	305	1052	0.3
138	257	322	1082	0.4
118	250	326	1106	0.5
102	234	330	1134	0.6
89	222	339	1150	0.7

NL, number of lane changes; RF, ramp to freeway.

In addition, the average delay improvements in terms of the percentage of those OD (Test 1 to Test 5) were drawn from the difference in delay time between the base case and the control case. Figure 8 indicates that the average delay improvement increased as the RF ratio increased. The number stood at approximately 28% when the RF ratio was at 0.3 and achieved its peak at the RF ratio 0.7 with around 56%.

4.3.3. *Tests for different penetration rates*

This section outlines how the strategy was influenced by different penetration rates. The penetration rate and the compliance rate are related to each other, such that the two terms are interchangeable. Therefore, this study considered only penetration rate. The rates of 5%, 10%, 20%, 40%, 60% and 80% were conducted.

Figure 9 shows the results with different penetration rates for RF ratios in terms of actual saving time, which expresses how many seconds the strategy has saved. **F9**

Overall, increased penetration received more positive benefits, as expected. Even with penetration rates as low as 5% or 10%, the strategy still achieved benefits. Compared with other studies, these results are quite noticeable. For example, a study by Park [22] showed that there was no significant improvement if the penetration rate fell below 70%.

Again, the figures also increased as the RF ratio increased. RF ratio 0.7 always had the most benefits among different RF ratios. With the expected travelled time (free-flow speed) of ramp vehicles and mainstream vehicles being 20.25 and 32.40 s, respectively, the maximum saved time, of almost 7 s in several cases, particularly in RF ratio 0.7, is remarkable.

In addition, the figures in the 60% penetration rate were seen to be very close to those in the 100% penetration rate. In other words, if the infrastructures were able to connect and give

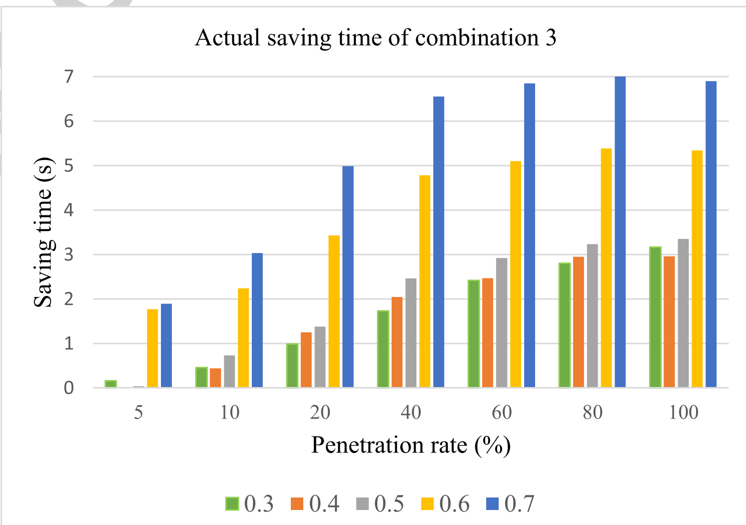

Figure 9. Actual saving times results for different penetration rates.

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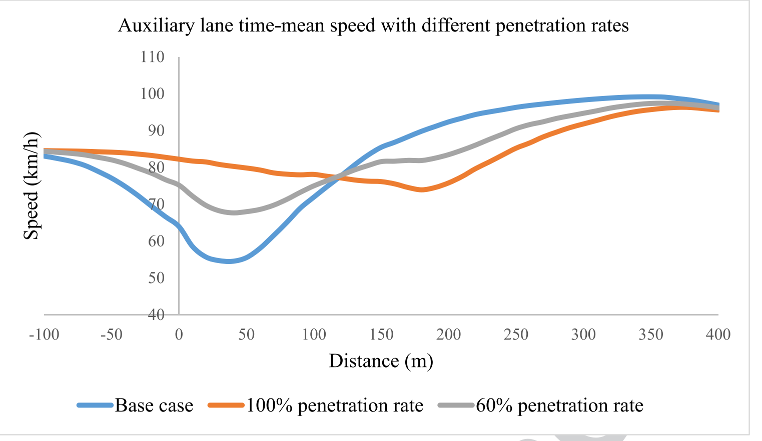

Figure 10. Auxiliary lane speed curve for different penetration rates.

instructions to 60% of the total vehicles, the predicted positive outcomes would be close to the fully connected scenario.

Figure 10 depicts how the speed was scattered over the auxiliary lane, with different penetration rates. According to Figure 10, the 100% time-mean speed curve had the flattest figure. Although the 60% penetration rate and the base case had a similar location of speed drop, Figure 10 clearly illustrates that the strategy reduced the impact of lane-changing concentration even with only a 60% penetration rate. **F10**

5. CONCLUSION

In this study, a lane-changing advisory application in weaving sections, based on C-ITS, was proposed and evaluated. The research motivations build on two main factors. Firstly, empirical findings indicate that drivers tend to merge or diverge quickly when they enter a weaving section, especially under capacity conditions. This proportion is very high and can be up to 90%. The behavior creates a bottleneck around the merge gore area, limiting weaving capacity, comfort and safety. Secondly, the advancement of wireless technology, as illustrated in the C-ITS, brings an opportunity to alleviate the problem. Vehicles are able to exchange information with infrastructures and vice versa. That is, individual vehicles could be monitored and advised through personalized messages, based on their destination lane. This research therefore proposes a lane-changing advisory strategy to achieve the full utilization of the entire weaving section using simple advice.

The following are the main findings of the study via the traffic simulation:

- The proposed concept has the potential to significantly reduce delay if the NL is spread out further downstream of the weaving section.
- Having the entire test scenarios classified as LOS E suggests that the advisory strategy works well when traffic volume is close to capacity. The bottleneck becomes more severe in this condition. Hence, applying the strategy to spread out the lane-changing density produces more benefits.
- If the total number of weaving vehicles is constant, varying the RF ratio will have significant impacts on the outcomes. The evaluation shows that the network becomes more efficient if the RF ratio increases.
- The results evaluation revealed that the increased penetration rate achieved more positive benefits, as expected. Even with low penetration rates (less than 20%), vehicles were still able to gain benefits. It was also found that the benefit of the 100% penetration rate was rather similar to that of the 60% penetration rate. In other words, if the infrastructures were able to connect and give instructions to 60% of the total vehicles, the predicted positive outcomes would be close to those of the fully connected scenario.

The results derived from this study are clearly related to the strengths and limitations of the AIMSUN software, and also rely on several assumptions. It is certain that field operational tests would provide

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the most reliable and accurate outcomes. Nevertheless, this study is one of the first to investigate the benefits of C-ITS in the coordination of vehicles in the lane-changing concentration in weaving sections.

The authors suggest a number of topics that can be considered as future work to make this research more comprehensive:

- The advisories in term of merging/diverging proportion and weaving lengths were taken manually in this study. It is necessary to optimize the lane-changing advisory proportion with respect to merging/diverging proportion and weaving length using an automatic system (i.e. implementing an algorithm or a control system).
- This study evaluates the effectiveness of the strategy based on the operational aspects. Because it is purely looking at the traffic efficiency side, traffic safety was not included within the study. A more comprehensive comparative analysis is desirable to capture the full picture of the strategy's influences by evaluating the effect of this C-ITS application on traffic safety – this can be evaluated by traffic simulator.
- The lane-changing advisory application assumes that the communication quality is reliable; however, there are many factors influencing the communication, such as uncertainty in measuring the location of the vehicles and delay in the communication of messages. A sensitivity analysis on how the communication quality can impact the network performance is necessary.
- As noted, the results derived from this study are clearly relative to the strengths and limitations of the AIMSUN software. Other simulation models can be applied to cross check the results. Additionally, the results would be more robust if the validation data were available. Hence, future studies and additional data are needed to capture the full impact of this C-ITS advisory application.

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