A C-ITS BASED LANE CHANGING ADVISORY FOR WEAVING SECTIONS

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Cooperative ITS, C-ITS, weaving bottleneck, weaving section management, lane change distribution, lane-change advisory, AIMSUN
Abstract

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. Characteristic of such sections is that they require extensive lane-change manoeuvres, one of the most risky manoeuvres that drivers have to perform in the motorway system. 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. Because of this high lane-changing concentration, congestion builds up. Importantly, such congestion also limits the use of existing infrastructure, the weaving section downstream. This behaviour thus affects both safety and operational aspects. Cooperative Intelligent Transport Systems (C-ITS) is the potential tool to manage motorways effectively and efficiently. This research investigates a lane-change distribution strategy 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 so that such lane-changing activities are evenly distributed over the existing weaving length. C-ITS will send a message to weaving vehicles, advising them when to execute a lane change.

The research applies a microscopic simulation in AIMSUN to evaluate the proposed strategy’s effectiveness in one-sided ramp weaves. The proposed strategy is evaluated with different traffic demands, weaving advisory proportions, penetration rates and weaving section lengths (400m and 600m).
The evaluation revealed that the proposed lane-changing advisory strategy has the potential to improve delay significantly and that it can be applied for any existing one-sided ramp weaves.
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<th>Description</th>
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<tr>
<td>API</td>
<td>Application programming interface</td>
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<tr>
<td>C-ITS</td>
<td>Cooperative Intelligent Transport Systems</td>
</tr>
<tr>
<td>FF</td>
<td>Freeway to freeway</td>
</tr>
<tr>
<td>FR</td>
<td>Freeway to ramp</td>
</tr>
<tr>
<td>LC</td>
<td>Lane change(s)</td>
</tr>
<tr>
<td>NL</td>
<td>Number of lane changes</td>
</tr>
<tr>
<td>RF</td>
<td>Ramp to freeway</td>
</tr>
<tr>
<td>RSU</td>
<td>Roadside unit</td>
</tr>
<tr>
<td>RR</td>
<td>Ramp to ramp</td>
</tr>
<tr>
<td>V2I</td>
<td>Vehicle to infrastructure communication</td>
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<td>V2V</td>
<td>Vehicle to vehicle communication</td>
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Statement of Original Authorship

The work contained in this thesis has not been previously submitted to meet requirements for an award at this or any other higher education institution. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made.

QUT Verified Signature

Signature: ______________________________

Date: 03/02/2015
Dedication and Acknowledgements

Dedication

The thesis is dedicated with love and passion to my parents, Toan and Chi, my love, Phan My, and to the Mai family.

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Chapter 1: Introduction

1.1 Background

Traffic congestion, a worldwide problem, strongly reduces traffic throughput, fluidity and safety, as well as increasing trip times and environmental pollution. In Australia particularly, the cost of congestion, estimated at around $9.4 billion in 2005, is expected to rise to over $20.4 billion by 2020 according to the Australian Government Department of Infrastructure and Regional Development [1].

The key for tackling traffic congestion is to match traffic demand and traffic network capacity (supply) by either reducing demand or increasing supply. Traffic demand, on the one hand, will keep increasing due to increases in population and car-ownership. Managing demand, such as increasing public transport, might work well in a high-density population area but might not be an effective method for a low-density area such as Australia. According to the literature [2], only 11% of the population take public transport as their main means of transportation. Increasing network capacity is a more commonly used approach for congestion management. Traditionally, constructing new infrastructure is considered to be the most straightforward way. However, this is becoming very difficult for limited financial funding and environment reasons. Vanderbilt [3] claimed that even though constructing more road is affordable, it is still not a good way to spend money because roads are uncongested most of the time. Therefore, intelligent transport systems (ITS) for maximising the utilisation of current infrastructure such as ramp metering (RM), variable speed limits (VSL), adaptive signal control and cooperative ITS (C-ITS) are of great benefit for managing traffic congestion.
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. Characteristic of such sections is that they require extensive lane change manoeuvres, one of the most risky manoeuvres that drivers have to perform in the motorway system [4]. These manoeuvres often cause turbulence, reduce travel speed, build up congestion and reduce weaving capacity.

A few approaches have been put into practice to manage these sections and to improve their operations, such as imposing speed limits [5] and modifying physical lane markings [6]. However, the improvements were insignificant (imposing speed limits) or lacked consideration of factors that influence weaving capacity (modifying physical lane markings). Hence, there are still opportunities for better management at these sections.

Thanks to the development of wireless technology, vehicles are now able to exchange information with other vehicles and infrastructures [7]. This emerging technology, the so-called C-ITS, offers a new way to increase traffic safety, productivity and efficiency.

This research seeks a possible way to manage the weaving sections of motorways with C-ITS, so that a comprehensive evaluation for reducing traffic congestion and conflicts can be achieved.

1.2 Research problem

As noted, 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.
Characteristic of such sections is that they require extensive lane change manoeuvres [4]. A lane change is a process involving a high level of interaction when vehicles manoeuvre laterally from one lane to another [8]. These interactions are difficult to predict because vehicles have to negotiate with the surrounding counterparts to perform lane changes [9]. Jula et al. [10] affirmed that the 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 (lane-changing 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 [4].

Weaving sections are also the main source of traffic bottleneck congestion [11], which can reduce traffic efficiency by 20% to 50% [12]. The bottleneck problem in weaving sections is the result of the concentration of merging and diverging manoeuvres. Empirical data have shown that drivers tend to perform lane changes close to the merge gore as the traffic volume increases: this behaviour builds up congestion. Hence, weaving manoeuvres affect the driving comfort, safety and operational aspects.

To alleviate the merging and diverging concentration problem, only one technique has yet been put into practice [6] (detailed information is provided in the literature review, section 2.1.4). However, this current technique is somehow not finding ways to utilize the entire weaving section. If the weaving length is used properly and in a coordinated way, travel time can be reduced and conflicts can be kept to a minimum.
1.3 Purposes and aim

The hypothesis for this research is that managing weaving sections with C-ITS can alleviate congestion and reduce travel time. The research questions are, therefore, as follows:

- How can the C-ITS improves the utilization of current infrastructure by vehicle-to-infrastructure communication?
- How is the C-ITS application influenced by penetration rates?
- At which traffic demand does the C-ITS provides the best measurement of effectiveness?
- What are the impacts of the proposed strategy on different weaving geometries?

The specific objectives of the research project are to:

- Review weaving sections and up-to-date weaving section management techniques.
- Review the nature of the C-ITS, including the advantages of cooperative systems, in order to reduce congestion and to increase traffic throughput at weaving sections.
- Propose a lane-changing advisory strategy for weaving vehicles.
- Investigate the proposed strategy with different traffic demands.
- Examine the impacts of the proposed strategy with different penetration rates and geometries.
1.4 Research Significance

The key components of this study are to utilize current existing weaving sections and to reduce travel time by organizing lane-changing actions and cooperation between vehicles and infrastructures. The research is expected to have both practical and scientific significance.

- Scientific significance: to the best of the author’s knowledge, this research is the first attempt to manage weaving sections with C-ITS. The achieved outcomes are also providing state-of-the-art knowledge in the C-ITS and weaving sections field.

- Practical significance: the proposed strategy, the lane-changing advisory, can be implemented in any existing one-sided ramp weaves. This will be a win-win process for drivers (less travel time) and for traffic operation authorities, whose main targets are to ensure the motorways networks run smoothly and to receive the maximum cost-effect when investigating any road infrastructure projects.

1.5 Thesis Outline

The thesis is outlined as follows. Chapter 2 reviews the existing knowledge on weaving sections, including the influencing factors on weaving capacity and driver behaviour at weaving sections. It also presents the nature of C-ITS and how it can assist in alleviating the problem at weaving sections. Chapter 3 details the methodology as well as the proposed strategy. Chapter 4 describes the simulation study, which includes the calibrated model and the simulation result analyses, each with different scenarios. Chapter 5 summaries the main findings by answering the research questions, before outlining suggestions of future works.
Chapter 2: Literature Review

The aim of this chapter is to provide the critical knowledge from the existing literature that will form the foundation for this study. This chapter first reviews the weaving section – the influenced factors on weaving capacity, the empirical data on weaving behaviour that causes the bottleneck problem, and weaving management techniques. Second, it outlines the Cooperative Intelligent Transport Systems (C-ITS) – the nature of C-ITS and its related characteristics. The final section of the chapter highlights the implications from the literature about how the C-ITS can assist in alleviating the problem in weaving sections, and develops the framework for the study in Chapter 3.

2.1 Weaving section

2.1.1 Weaving section definition

The Highway Capacity Manual 2010 [13] defines weaving sections as:

Sections in which two or more traffic streams travelling in the same general direction cross paths along a significant length of freeway without the aid of traffic control devices (except for guide signs). Weaving sections are formed when a diverge segment closely follows a merge segment or when a one-lane off-ramp closely follows a one-lane on-ramp and the two are connected by a continuous auxiliary lane.

The terms ‘weaving’, ‘merging’, and ‘diverging’ are sometimes unclear as their individual meaning are difficult to isolate. Roess et al. [14] defined the differences among these terms:
Weaving occurs when one movement must cross the path of another along a length of facility without the aid of signals or other control devices. Such situations are created when a merge area is closely followed by a diverge area. Merging occurs when two separate traffic stream join to form a single stream, while diverging occurs when one traffic stream separates to form two separate traffic streams.

Weaving sections are classified into two different types, one-sided and two-sided, based on their configurations and the minimum amount of lane changing required. This research, however, focuses only on one-sided weaving sections, in which no weaving manoeuvres require more than two-lane changes to be completed successfully and all the weaving movements are taken on one side of the section.

The geometry of the one-sided ramp weave, where a one-lane on-ramp is followed by a one-lane off-ramp, with a continuous auxiliary lane between the ramps, is illustrated in Figure 1. Note that the case of an on-ramp followed by off-ramps that are not joined by a continuous auxiliary lane is not considered to be a ramp-weaving section. It is treated as separate merge and diverge areas [15].

![Figure 1: One-sided ramp weaving section](image)

A weaving section always has four different flows: the two that cross each other’s path are weaving flows; those that do not are non-weaving flows. As drawn in Figure 2, vehicles entering on leg A and exiting on leg D cross the path of vehicles entering on leg B and exiting on leg C. These are the weaving flows. Movement A-C
and B-D do not have to cross the path of any other movements, even though they may share lanes, and they are referred to as non-weaving flows.

![Diagram of weaving and non-weaving flows]

Figure 2: Weaving and non-weaving flows

where:

- BD: Freeway to freeway flow (FF)
- AD: Ramp to freeway flow (RF)
- BC: Freeway to ramp flow (FR)
- AC: Ramp to ramp flow (RR)

### 2.1.2 Factors influencing weaving capacity

Many factors influence weaving capacity: in particular, volume ratio, weaving ratio, weaving width and length of weaving and traffic flow composition. This section outlines the characteristic of these.

#### 2.1.2.1 Volume ratio

Volume ratio (VR) is the ratio of the total weaving volume to the total flow entering the section. It is represented by $VR = \frac{V_{BC+AD}}{V_{Total}}$.

#### 2.1.2.2 Weaving ratio

The weaving ratio (R) is defined as the ratio of the smaller weaving flow rate to the total weaving flow rate. It is represented by $R = \frac{V_{AD}}{V_{AD+BC}}$ or $\frac{V_{BC}}{V_{AD+BC}}$. 
2.1.2.3 Weaving width

The weaving width of a weaving segment is measured as the number of continuous lanes within the segment, that is, the number of continuous lanes between the entry and exit gore areas [13].

As the number of lanes increases, this not only creates opportunities for lane changing, both in mandatory and discretionary lane changes, but also helps to reduce overall densities and to increase the throughput capacity. At the same time, the opportunity for lane changing also increases for discretionary lane changes that may take place within the weaving section [16]. The weaving width of the weaving section in Figure 3 is 4.

![Weaving width and length of the weaving section](image)

2.1.2.4 Weaving length

Weaving length (Figure 3) is the length from a point on the merge gore at which the right edge of the freeway shoulder lane and the left edge of the merging lane are 0.6m apart to a point on the diverge gore at which the edge are 3.7m apart [13].

The weaving length influences the time and space that drivers have to perform lane changes. Therefore, if the weaving length is decreased while other factors remaining constant, drivers take more time to look for limited acceptance gaps for
lane changes. As a result, this creates turbulence and reduces the travel speed and the weaving capacity [17].

In their study of one-sided weaving sections, Fitzpatrick and Nowlin [18] suggested that weaving sections should be operated at a minimum of 200m, even though a weaving section at 300m is desirable. Their reason is that traffic starts to break down quicker with weaving section in which the weaving length is less than 200m.

However, Vermijs [19] proved that even though the weaving length helps to increase weaving capacity, it has no or minimum impact on the capacity when it reaches a specific length. It has been shown that weaving section more than 400m had no significant impacts on weaving capacity.

2.1.2.5 Traffic flow composition

Traffic flow composition also affects weaving capacity. Other vehicle types such as heavy vehicles, high occupancy or buses often take up more space and require more time to complete the weaving due to their relatively slow speeds and acceleration. Vermijs [19] has verified that when the percentage of truck increases by 5%, weaving capacity decreases by approximately 8%.

2.1.3 Driving behaviour in weaving sections

This sub-section describes the driving behaviour in weaving sections that caused the concentration problem.

Cassidy et al. [20] 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 occur near the merge gore. To be more specific, they found that the majority of lane changes (LC) were made in the first 73m of a 445m weaving section. The same behaviour was found even where the weaving length is relatively
long. This behaviour tends to increase when the flow rate increases because drivers become more anxious to change lanes over the short 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. [21] studied weaving behaviour by investigating its characteristics at a 129m one-sided weaving section. The video analysis demonstrates that most of the LC took place at the first half (65m) 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, 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 [22] examined the capacity and quality of service of several weaving sections in California. Their two hours of video data proved that weaving vehicles tried to execute LC 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 120m to 150m of the 400m weaving sections. As a result, a queue formed near the merge gore while the weaving section downstream is starved for demand.

Another study was conducted by Ho Lee [15] to investigate the bottleneck at weaving section. One important observation that came out of this research was that the tendency of diverging vehicles to change lane close to merge gore areas is 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 change lane close to the merge gore increases, the bottleneck becomes more severe.

The latest empirical data was investigated by Al-Jameel [23]. Within that research, the author divided the 400m weaving section into four segments from the merge gore (0-50m, 50-100m, 100-150m and >150m) and explored the lane-changing location. The research found that approximately 80% of merging vehicles and up to 90% of diverging vehicles completed LC in the first 100m of the 400m weaving section.

In summary, this sub-section outlines the driving behaviour in weaving sections. One can see that drivers are more likely to change lane as close to merge gore as possible when they enter the weaving section. This behaviour creates a very high lane-changing concentration, up to 90%. Thus, congestion builds up, limiting weaving capacity. The next section presents the up-to-date weaving section management techniques.

2.1.4 Weaving section management techniques

The bottleneck that is formed by the concentration of weaving vehicles is a clear problem and better use of the existing infrastructure seems to be the effective solution.

Only one technique has been used in weaving sections to alleviate the concentration of merging and diverging vehicles close to merge gore areas up to date even though there are many literatures that have examined the lane-changing behaviour at weaving sections. This is because the lane changing at weaving sections is a complicated process that involves a high level of interactions when vehicles manoeuvre laterally from one lane to another [8]. Al-Jameel [6] has proposed a method that shifts diverging vehicles to the end of the auxiliary. A solid line marked
on the left side on the shoulder lane at the weaving section has been added on the auxiliary lane (Figure 4). Merging vehicles are allowed to move to mainline at all times if an acceptable gap is available. Diverging vehicles will be able to execute lane changes to auxiliary only when passing the solid line. From the solid line lengths tested, the 150m solid length, which increased weaving capacity by 5% (from 7050 vph to 7400 vph) was found to be optimum.

Figure 4: Al-Jameel's weaving management technique [6]

2.2 Cooperative Intelligent Transport Systems

C-ITS is a new form of intelligent transport systems (ITS). Different from other ITS, the C-ITS is an emerging technology that enables vehicles and surrounding infrastructures to exchange information in real time about the location, speed and direction of other road users also using C-ITS. This has the potential to provide a myriad of applications, including delivering safety, productivity, efficiency and environmental outcomes [7]. With the rapid development of communication technologies, C-ITS is attracting more and more attention, not only from academics but also from road agencies. Powered by wireless communication in real time, C-ITS offers new opportunities for collecting traffic data and managing traffic at an individual level rather than at a flow level.
Firstly, C-ITS is able to measure individual vehicle data containing rich information. Compared with traditional point data measures (e.g. loop detector), individual vehicle data can provide better-aggregated measurement of traffic flow (i.e. flow, speed and headway). More importantly, C-ITS is able to directly measure density, the most useful and stable measurement for traffic control systems, such as ramp metering (RM) and variable speed limit (VSL). A real time origin-destination (OD) matrix, another important input for traffic control systems, can also be well estimated based on individual data collected from C-ITS. Besides, individual vehicle data are the best source for studying driving behaviours and traffic flow modelling (especially for the bottleneck sections, such as the merging and weaving sections).

Secondly, C-ITS can regulate each individual vehicle for both traffic safety and efficiency according to its surrounding traffic conditions. By monitoring distances from surrounding vehicles, C-ITS can improve traffic safety by preventing crashes. C-ITS can also contribute to traffic efficiency. For example, in the case of the merging areas on motorways, Park [24] stated that not taking the actual individual vehicles into account creates non-smooth merging actions due to the non-distributed gap at the merging area. Some cars may have more room to merge; others have to wait due to a lack of gaps, which reduces the total motorway capacity, making it underutilized. With C-ITS, the whole merging process can be cooperative between ramp vehicles and mainline vehicles to maximise the total capacity.

C-ITS provides services to all road users and operators [7]. The two primarily connections through wireless communication are:

- Vehicle-to-vehicle (V2V) connection
- Vehicle and infrastructure, roadside unit, (V2I) connection
2.2.1 Levels of C-ITS assistance

The main differences among the systems are driver reaction time, a substantial factor in preventing lane change crashes, and the degree to which functions are taken over by the system rather than left for the drivers. The U.S. Department of Transportation [4] has identified four different levels of C-ITS assistance on driving behaviour.

- Driver information systems: provide drivers with information regarding traffic state and driving environment. However, as the warning signs are not included, drivers are responsible for judging whether/when it is safe to make a lane change.

- Advisory/cooperative systems: unlike the driver information systems, these types of applications include warning safety messages when certain thresholds are exceeded. The safety messages are forwarded to affected vehicles to warn about the presence of other vehicles in the adjacent lanes. Instructive messages are also sent to drivers to advise them in dealing with the situations (i.e. brake and/or decelerate).

- Semi-automatic systems: to avoid crashes, vehicles will be partially controlled in critical situations to avoid crashes by locking a part of the vehicle components, such as the brake or accelerating pedal. After crossing the potential hazard, drivers remain responsible for their driving.

- Fully automatic control systems: the highest level of C-ITS assistance, to control the vehicle fully and automatically, means that the required reaction time is (nearly) zero. The strategy involves fully automatic braking, automatic steering, and throttle control without driver intervention.
It is proposed that a cooperative system will be implemented in this study, rather than a (semi) automatic system. The author believes that there is still a long way to go until fully automatic control can be implemented. Hence, a cooperative system should be the next step to build the foundation in the field.

2.2.2 Types of C-ITS communications

Vehicle to vehicle (V2V) and vehicle to infrastructure (V2I) are two different communication links of C-ITS. This section outlines the main characteristics, advantages and disadvantage of these links. From this judgment, the type of communication link is selected for the study.

V2V, by its name, has the ability to communicate directly with other vehicles. Hence, this enables a number of safety applications. These types of applications alert drivers to the potential dangers, to increase their awareness and to avoid unforeseeable accidents. V2V can communicate with other vehicles for a small to medium distance (300m to 1000m) without the aid of roadside unit (RSU) in a fast and reliable channel [25].

However, it is the driver’s responsibility to decide the relevance and the appropriate actions (i.e. what to do when they receive the forward collision warning). Another problem of V2V communication is that it is not very useful if the number of equipped vehicles is low [26].

Vehicles can also communicate with infrastructures via RSU and vice versa to form a V2I link. With the V2I communication link, RSU can forward personalized messages to targeted groups of vehicles for better traffic management. In addition, the communication range can be extended by the connections among RSUs, which is very useful for traffic efficiency and traffic coordination applications [27].
The drawback of the V2I link is that the supported infrastructures are not currently available so would require additional cost for their installation [26]. To increase its efficiency, it can be installed first at the hot spots, such as on-ramps, off-ramps or weaving sections.

Choosing which type of C-ITS communication connection depends on the application type and the link’s characteristics. Since the scope of this project is to increase traffic efficiency by better coordination between vehicles, this study will implement V2I as the primary communication link. Table 1 summarises the types of C-ITS communications.

Table 1: Types of C-ITS communications

<table>
<thead>
<tr>
<th></th>
<th>V2V</th>
<th>V2I</th>
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<tr>
<td><strong>Advantages</strong></td>
<td>Direct communication between vehicles (lower noise);</td>
<td>Provide a longer communication range;</td>
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<td></td>
<td>Useful in locations where RSU are not available;</td>
<td>Provide a wide range of applications rather than safety applications (i.e. safety, mobility, efficiency and driver’s comfort);</td>
</tr>
<tr>
<td></td>
<td>Suitable for C-ITS safety applications.</td>
<td>Act as the information distributor;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Offer better traffic prospective.</td>
</tr>
<tr>
<td><strong>Disadvantages</strong></td>
<td>Mostly apply for safety applications;</td>
<td>Need to construct road side units;</td>
</tr>
<tr>
<td></td>
<td>Driver responsibility for their reactions;</td>
<td>Indirect communication link (i.e. vehicles forward messages to infrastructures before receiving information or instructions).</td>
</tr>
<tr>
<td></td>
<td>Limited communication ranges.</td>
<td></td>
</tr>
</tbody>
</table>

**2.2.3 C-ITS evaluation**

This section discusses how to evaluate the implementation of C-ITS applications. The three main methods are traffic simulation, driving simulator and field test.
2.2.3.1 Traffic simulation

Traffic simulation, the most common method of evaluating C-ITS applications, will be the best candidate to test any new strategies on the road because it is cost-effective. Other benefits of using traffic simulation include no legal or safety concerns, and full controllability and flexibility of the test scenarios [28]. Specifically, a field experiment usually involves a limited number of participants, which raises the legal and safety issues; and some of the test scenarios, such as a different percentage of compliance rates, are difficult to be controlled and tested with field experiment.

Generally, traffic models are categorised as microscopic, mesoscopic and macroscopic [29]. Different models present different levels of detail of traffic flow: the microscopic model is based on car-following and lane-changing models of individual vehicles; the mesoscopic model looks at the behaviour of a platoon; and the macroscopic model considers only aggregated traffic flow features, including flow, density and speed [29]. The microscopic model is the most appropriate for assessing C-ITS applications because it has the resolution of analysing the impact on individual vehicles [30]. The drawbacks of the microscopic model are the accuracy of interpreting driver behaviour and the difficulty in calibration and validation, as well as the difficulty in assessing traffic safety [29].

2.2.3.2 Driving simulator

The driving simulator is a tool to model a realistic driving environment. The main objective of deploying a driving simulator for a C-ITS application is to evaluate the impact on safety and driving behaviours in a risk-free environment. It is therefore a suitable method to test in the field any new applications, which are dangerous and difficult to test. The simulator ensures drivers experience the same situation and
realistic driving conditions with guaranteed safety, which also ensures the tests could be repeated several times without putting in too much work, compared to field testing [31]. The test can be done with a range of different vehicle types such as passenger cars, trucks or commercial vehicles.

The disadvantage is that the test cannot be used for a large-scale experiment. Normally, there is only one vehicle with a simulated driving environment available at one time. Another disadvantage is that some of the negative effects recorded by the simulator, such as sickness and discomfort (not all participants feel the same effects), affect the accuracy of the results. Consequently, there is some disagreement between driving simulators and the real data obtained [32]. The driving simulator has been implemented in many big projects in Europe, such as COOPERS and CVIS.

2.2.3.3 Field operational test

A field test is the ultimate way of evaluating C-ITS because it provides the real situations and environment, which means the results are reliable and accurate. Willke et al. [33] stated that much research is based on oversimplified networks and models, which emphasizes the importance of field tests in the evaluation step. However, field testing is usually costly and time-consuming, preparing the test equipment and carrying out large-scale experiments. In addition, safety is always a concern for field tests. Few projects so far have had the C-ITS application assessed by large-scale field tests. Table 2 provides a comparison of different C-ITS evaluation methods.
Table 2: Comparison of C-ITS evaluation methods

<table>
<thead>
<tr>
<th>Types of C-ITS evaluations</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traffic simulation</td>
<td>Minimum cost; Full controllability and flexibility of test scenario</td>
<td>Difficulty in model calibration; Difficulty in assessing safety application</td>
</tr>
<tr>
<td>Driving simulator</td>
<td>Assessment of safety application in a controlled and safe environment; Driving behaviour can be observed and controlled</td>
<td>No large-scale experiment; Negative effects (such as sickness, discomfort) influence the accuracy.</td>
</tr>
<tr>
<td>Field test</td>
<td>Most reliable and accurate results</td>
<td>Expensive, time-consuming and safety concerns</td>
</tr>
</tbody>
</table>

### 2.2.4 Penetration rate

Penetration rate, the rate of the number of vehicles equipped with communication devices versus all vehicles, is critical for the success of a C-ITS application. This sub-section firstly presents the status and trend of the market rate of equipped vehicles, which profoundly affects the penetration rate in the field. The required rate to ensure the success of C-ITS applications is then discussed.

#### 2.2.4.1 Market rate

According to The United States Department of Transportation, the deployment of equipped light vehicles in U.S. in 2014 and 2015 is predicted to be 75% and 100% respectively [34]. This means that every new light vehicle manufactured in 2015 will be equipped with the system. These rates represent only the new manufactured vehicles, not the rate of the whole market. Aftermarket vehicles remain in the U.S. until they are replaced with new ones. The percentage forecast of equipped vehicles in U.S., combining the aftermarket vehicles and the assumed equipped vehicles, is illustrated in Figure 5.
This figure shows the estimation of equipped light vehicles in US from 2006 to 2054. Overall, there is an increase in trend; however, the degree of increment is very different. For example, the whole market of connected vehicles in the U.S. is estimated to be approximately 10% in 2014 and is forecast to jump to almost 50% in 2020 and more than 90% in 2031, while the predicted figure after 2031 increases gradually until it reaches 100% in 2046. This indicates a promising market rate.

Another strategy, called the aftermarket penetration rate, considers not only equipped vehicles but also vehicles coupled with other on-board units. Smart phones coupled with GPS transmitters are a common option. However, the shortage of bandwidth and the battery life limit its implementation [35]. Another option is the ‘integrated’ solution, an add-on solution which requires an installation of a small device into the On-Board Diagnostic systems (OBDII) inside a vehicle and on the Human Machine Interface [36].

**2.2.4.2 Penetration rate for C-ITS applications**

When considering the C-ITS required penetration rate, we consider only the vehicles that are equipped with the communication device and are following the
instructions forwarded by the C-ITS applications. In the rest of this section, the effective penetration rate is used to measure the C-ITS required penetration rate. Every application requires a down-mark penetration rate before showing the positive effects sufficiently. Among these, safety applications require a higher penetration rate than other types of C-ITS applications [36].

An effective penetration rate is an important factor that has a prominent influence in the implementation of the C-ITS [37]. After investigating the early lane changing advisory and the lane merging on-ramp through infrastructure to vehicles communication, Park et al. [38] concluded that there is a very small improvement in the merging throughput if the effective penetration rate falls below 90%, and there is no significant improvement if the rate falls below 70%.

In the case of the dynamic speed advisory, Carlson et al. [39] showed that the required penetration level of equipped vehicles can be a small proportion because the equipped vehicles will act as leaders in the platoon in the lane, so the following cars will have to adjust their speed according to the speed of the leaders. However, there could be an accident risk if only small numbers of vehicles receive the messages (i.e. congestion or roadwork ahead) while others do not. Silvano, Farah and Koutsopoulos [40], in their simulation of I2V in the COOPER project, calibrated that after receiving information regarding the traffic state, the received message vehicles reduce their driving speed, thus becoming “obstacles” to following vehicles without the systems.

The penetration rate fluctuates between different research studies and applications. Thus, the penetration rate will therefore be carefully tested and analysed when developing a new strategy within the study.
2.3 Summary

The literature review reveals that a bottleneck problem in the weaving section results from the merging and diverging manoeuvres concentration. Hence, the entire length of the weaving section is not used effectively or fully used.

Having better use of the shoulder lane and auxiliary lane is one of the best ways to tackle the concentration problem. To the best of the author’s knowledge, there is only one technique that investigated the problem by adding the physical markings: that outlined in [6]. However, this technique controls only weaving vehicles from mainstream or on-ramp and does not take into account other factors influencing weaving capacity, such as weaving ratio, weaving volume and weaving length. Once the physical marking is drawn, it is applied for all cases.

On the other hand, with C-ITS, vehicles and infrastructures are able to exchange information in real time. Personalized messages can be sent to advise individuals or the targeted groups of vehicle. In other words, C-ITS can coordinate and distribute the weaving vehicles into the existing infrastructure dynamically; other factors (ratio, volume, length) are also considered.

In short, C-ITS offers an opportunity to address the lane-change concentration problem, which is mostly created by weaving vehicles at the weaving section. C-ITS will send personalized guidance/messages to advise weaving vehicles based on their destination lanes. By doing so, the lane-changing concentration problem can be alleviated, and the whole weaving section can be fully utilised.
Chapter 3: Methodology and the proposed strategy

This chapter first describes the methodology adopted in this research to achieve the aims and objectives stated in Chapter 1 – to utilize the current existing weaving section via distributing lane changing actions and cooperation between vehicles and infrastructures – and the stages by which the methodology will be implemented. The last section details the study’s proposed strategy based on the Cooperative Intelligent Transport System (C-ITS).

3.1 Research methodology
The research approach is planned in the following stages, depicted in Figure 6.
Step 1: Literature review

The first stage of the literature review focuses on weaving sections with an in-depth overview, including the factor influencing weaving capacity and its current management methods. The second section of the literature gains insight into C-ITS. In short, the discovered goals of the literature reviewed in Chapter 2 are to:

- Provide the evidence of lane-change concentration problems of traffic at weaving sections;
• Outline the nature of C-ITS and how it can assist to alleviate the weaving section bottleneck, created by weaving vehicles.

Step 2: Research methodology and the developed strategy

A strategy based on the nature of C-ITS and the current problem with lane changing at weaving sections will be proposed to lessen the problem and to reduce travel time. This step is outlined in section 3.2 in this chapter.

Step 3: Simulation and results analyses

After the strategy is proposed, it is carefully implemented and evaluated via the micro-simulation AIMSUN using code written in Python. Performance indicators will be examined and chosen based on the current literature. The simulated results will be compared with those in the base case (uncontrolled case). Chapter 4 presents the details of this step.

During this evaluation, conclusions will be drawn to prove the hypothesis and answer the research questions.

Step 4: Conclusion and recommendation for future works

The last step of the research plan is to present the research findings by answering the research questions. Recommendations for further works are also included. These steps are outlined in Chapter 5.

3.2 The proposed strategy

As outlined in the literature review section, a very high number of lane-change manoeuvres occur close to the merge gore area, especially when the traffic flow is close to capacity. That 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.

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 travel time.

The scenario is the one-sided ramp weave, which has three main lanes and one auxiliary lane as shown in Figure 7. The weaving section is divided into a few different small segments and each segment contains a particular weaving length. While non-weaving vehicles travel as normal, weaving vehicles are advised to make a lane change when they reach a particular reference segment in the weaving section.

![Figure 7: Weaving section geometry](image)

The lane-change advisory strategy flowchart outlined in Figure 8 includes four steps:
Figure 8: Lane-changing advisory strategy for weaving vehicles

**Step 1: Data collection**

The purpose of this step is to collect OD information when a vehicle enters the weaving section. This is for identifying weaving and non-weaving vehicles. It is proposed that this step is done 1000m further upstream from the section entrance point, to ensure weaving vehicles have enough time to react to the instructions.

**Step 2: Categories vehicles**

This step aims to categorize non-weaving and weaving vehicles.

**Step 3: Grouping weaving vehicles**

If an entering vehicle is a non-weaving vehicle, the strategy will do nothing.
If a vehicle enters the system as a weaving vehicle, it will be assigned a random number (from 0.0 to 1.0). Weaving vehicles are gathered into different groups based on this random number (uniformly distributed), with each group containing a distinct weaving vehicle percentage.

**Step 4: Lane changing distribution for weaving vehicles**

This step aims to advise weaving vehicles of the segment where they can start executing a lane change. For example, the first weaving vehicle group (group A) can start to change lanes when they enter the weaving section once they get a proper gap, the second group should not manoeuvre to another lane until they reach the second segment (segment B) in the weaving section. The third group of weaving vehicles should change lane starting from the third segment (segment C) in the section, and so forth.

Note that the lane changing is still governed by the AIMSUN lane-changing model. Weaving vehicles are not forced to change lane at the specific segment; they are, in fact, encouraged to perform a lane change from a particular reference segment in the weaving section.

**3.3 Chapter summary**

The chapter presents the methodology used within the study before the research strategy is illustrated. Details of the development and the result analysis are presented in Chapter 4.
Chapter 4: Simulation and evaluation of weaving section

This chapter first outlines the simulation test bed and different test scenarios, then presents and discusses the evaluation results.

4.1. Simulation test bed and different test scenarios

4.1.1 Simulation test bed

The tests are evaluated by the commercially available microscopic traffic simulation AIMSUN (Advanced Interactive Microscopic for Urban and non-urban Network). The software was developed by Transportation Simulation System (TSS) at the Universidad Politecnica Catalunya (UPC), Spain [41]. This powerful microscopic traffic simulation software makes building the model an easy task, with errors kept to a minimum. AIMSUN also offers the application programming interface (API) functions, 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.

The simulation period is 60 minutes, with a 15 minutes warm-up. To ensure the test’s credibility, each of the tests was run with 20 different replications. The result is 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 number of lane changes (NL) in the weaving section. Therefore, the tested network and the adopted data\(^1\) are taken from Al-Jameel’s research paper [23]. The network, a 400 m one-sided ramp weave, has the following traffic flow rate:

---

\(^1\) In Al-Jameel [22], data provided in the line graphical form, which outlined the traffic volume and the relative NL in different small segments of the weaving section.
• Freeway to freeway (FF): 5300 vph
• Freeway to ramp (FR): 900 vph
• Ramp to freeway (RF): 900 vph
• Ramp to ramp (RR): 100 vph

It is worth noting that the above traffic flow rates consider cars only and heavy vehicles (such as trucks) are not included.

Calibration is the next 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 condition being modelled [41]. The data set available for calibration is the NL in the weaving section.

NL in the weaving section: Al-Jameel [23] investigated NL in terms of percentage in the weaving section by using video to capture the behaviour. With the 400m weaving section, the author divided the weaving section into four different segments, namely A (50m), B (50m), C (50m) and D (250m), and recorded the NL (of weaving vehicles) in each segment;

The model can represent the merging and diverging concentration problem by adjusting the ‘distance to zone’ parameters in AIMSUN. The default and calibrated values are shown in Table 3. Other parameters, such as lane-changing cooperation and side-lane merging distance, were also adjusted. However, no significant difference was observed.
Table 3: Default and calibrated values in AIMSUN

<table>
<thead>
<tr>
<th>Road types</th>
<th>Motorway</th>
<th>On/off ramp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>Default value</td>
<td>Calibrated value</td>
</tr>
<tr>
<td>Distance to zone 1 (m)</td>
<td>500</td>
<td>650</td>
</tr>
<tr>
<td>Distance to zone 2 (m)</td>
<td>100</td>
<td>450</td>
</tr>
</tbody>
</table>

The NL in terms of percentage of the observed and calibrated values are revealed in Table 4. The data demonstrate that the calibrated values are close to the observed values. This is also the best attempt that has been achieved among numerous simulation runs. The test bed is now ready for comprehensive results analysis with different test scenarios.

Table 4: Number of lane changes in the weaving section (observed and calibrated values)

<table>
<thead>
<tr>
<th></th>
<th>Merging vehicles</th>
<th>Diverging vehicles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Segment</td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>Observed value (%)</td>
<td>45</td>
<td>38</td>
</tr>
<tr>
<td>Calibrated value (%)</td>
<td>40</td>
<td>50</td>
</tr>
</tbody>
</table>

4.1.2 Test scenarios

To implement the strategy, some initial assumptions are made:

- The C-ITS application is coupled with 100% penetration rate (this rate changes when different penetration rates are tested);
- Every vehicle follows the guidance given by the infrastructure;
- Every vehicle within the communication zone will be tracked by RSU so their destination lanes are identified.
- The communication signal strength is 100% guaranteed;

The result is evaluated between two different cases:
• Base case: the case without applying the strategy in which the bottleneck occurred;

• Control case: the lane-changing advisory applied for weaving vehicles.

Four different scenarios will be investigated as shown in Table 5. As mentioned in the proposed strategy (section 3.2), the objective of the strategy is to distribute the weaving proportion further downstream of the weaving section, to eliminate the bottleneck occurring near the merge gore area. In scenario 1, for 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 manoeuvre 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 (50m from merge gore).

• Similarly, 15% of weaving vehicles are encouraged to change lane when approaching segment C in the weaving section (100m from merge gore).

• Finally, 40% of total weaving vehicles should perform a lane change in segment D only (150m from merge gore).
The ultimate goals of scenarios 1, 2 and 3 are to test how the strategy varies with different lengths and lane-change advisories; scenario 4 tests the strategy with different weaving section lengths (400m versus 600m).

4.2. Performance indicators

Choosing appropriate indicators to evaluate the weaving section is vital [42]. Previous research has often viewed the average vehicle speed as one of the operational indicators. However, Cassidy and May (6) found that average vehicle speed does not always reflect the section operation. When the relationship between the speed and volume-capacity (V/C) was plotted, it was observed that the speed was insensitive to the high flow [43]. This is further explained by Denny and Williams [22], who stated that because of the bottleneck formation, speed would be lowest close to the merge gore areas where the maximum interaction between merging and diverging vehicles occurs. The speed will increase once they move through the

Table 5: Different test scenario parameters

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Segment</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>Total weaving section</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Length (m)</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>250</td>
<td>400m</td>
</tr>
<tr>
<td></td>
<td>Lane changing advisory proportion (%)</td>
<td>30</td>
<td>15</td>
<td>15</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Length (m)</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>250</td>
<td>400m</td>
</tr>
<tr>
<td></td>
<td>Lane changing advisory proportion (%)</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Length (m)</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>160</td>
<td>400m</td>
</tr>
<tr>
<td></td>
<td>Lane changing advisory proportion (%)</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Length (m)</td>
<td>120</td>
<td>120</td>
<td>120</td>
<td>240</td>
<td>600m</td>
</tr>
<tr>
<td></td>
<td>Lane changing advisory proportion (%)</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td></td>
</tr>
</tbody>
</table>
bottleneck location. Hence, speed will not be used as an operational performance indicator in this research. Instead, speed shows how smooth drivers cross the weaving section and observes whether the concentration of merging and diverging problem has been alleviated successfully.

Instead of applying average speed as the operational indicator, this study adopts average delay, which is calculated as the difference between the actual travel time and the free-flow travel time. Actual travel time is recorded by API, which collects the travel time of individual vehicles passing the network and then calculates the average delay. The free-flow travel times of the mainline vehicles (FF and FR) and the on-ramp vehicles (FR and RR) are calculated to be speeds of 100 km/h and 80 km/h respectively. For mainline vehicles, the actual travel time is calculated from 500m upstream from the merge gore to downstream where vehicles pass the weaving section, while this number for on-ramp vehicles is recorded as 130 m from the merge gore to the weaving section downstream. The unit of average delay time is second per vehicle (sec/veh).

Another operational indicator is the actual saving time, which indicates how many seconds the strategy has saved. The unit of actual saving time is second per vehicle (s/veh).

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

- To understand how smooth drivers cross the weaving section:
  - Speed over the weaving section (km/h)

- Operational indicators:
  - Average delay time (s/veh)
  - Actual saving time (s/veh)
4.3 Simulation results and discussion

4.3.1 Evaluation of scenario 1

Table 6 lists the actual percentage NL that occurred in each small segment in the weaving section after the strategy was implemented. For merging vehicles, for example, 8% of the allowed 30% found a gap and changed lane in segment A. This means that another 22% of merging vehicles performed a lane change in either segment 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 (150m from the merge gore).

Table 6: Actual merging and diverging proportion

<table>
<thead>
<tr>
<th>Segment</th>
<th>Merging vehicles</th>
<th>Diverging vehicles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual lane change (%)</td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>26</td>
</tr>
</tbody>
</table>

Detailed average delays with different movements are demonstrated in Table 7. Overall, every vehicle in the network experienced significant reductions of different degrees in delay time. For example, the expected travel time of FF vehicles is 32.4 seconds while the delay in base case and in control case are 9.44 and 5.33 seconds proportionally. This results in a 44% delay reduction or a 12.7% travel time reduction. The FF vehicles also achieved the maximum benefit compared to other movements.

Similarly, this number for FR, RF and RR are 41%, 24% and 29% respectively. As a result, the average delay time per vehicle in the network dropped 42% (from 9.11 seconds to 5.58 seconds).
Table 7: Delay improvement

<table>
<thead>
<tr>
<th>Movement</th>
<th>FF</th>
<th>FR</th>
<th>RF</th>
<th>RR</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected travel time (s/veh)</td>
<td>32.4</td>
<td>32.4</td>
<td>20.25</td>
<td>20.25</td>
<td>28.18</td>
</tr>
<tr>
<td>Delay in base case (s/veh)</td>
<td>9.44</td>
<td>14.06</td>
<td>5.93</td>
<td>3.93</td>
<td>9.11</td>
</tr>
<tr>
<td>Delay in control case (s/veh)</td>
<td>5.33</td>
<td>8.25</td>
<td>4.49</td>
<td>2.79</td>
<td>5.58</td>
</tr>
<tr>
<td>Delay improvement</td>
<td>44%</td>
<td>41%</td>
<td>24%</td>
<td>29%</td>
<td>42%</td>
</tr>
</tbody>
</table>

The standard deviation between the delay in the base case and the delay in the control cases is illustrated in Table 8, which shows that delays in the control cases achieved smaller values compared to delays in the base case. It indicates that delays in control cases are more consistent in comparison with delay in control case.

A 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 is that there is no difference between the delay in base case and the delay in control cases. Table 8 demonstrates the critical probability value (p value) at 5% significance level of four different movements in the weaving section. Since the p values of all movements are less than 0.05, the null hypothesis is rejected. In order words, the intervention of the C-ITS lane-changing advisory application significantly reduces the delay in the weaving section.

Table 8: Statistical significance of the delay in base case and delay in control case

<table>
<thead>
<tr>
<th></th>
<th>FF</th>
<th>FR</th>
<th>RF</th>
<th>RR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard deviation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Delay in base case (s)</td>
<td>7.0</td>
<td>8.1</td>
<td>3.8</td>
<td>3.8</td>
</tr>
<tr>
<td>Delay in control case (s)</td>
<td>4.5</td>
<td>5.5</td>
<td>2.9</td>
<td>2.2</td>
</tr>
<tr>
<td>Critical Probability Value (5% significant level)</td>
<td>1.1E-159</td>
<td>6.3E-44</td>
<td>5.1E-20</td>
<td>3.3E-03</td>
</tr>
</tbody>
</table>
Figure 9 illustrates the speed contours of the auxiliary lane and lane 3 (shoulder lane), in which most of the turbulences in the weaving section occur. The speed contour plots are not intended to measure the operational effectiveness. In fact, they show that the concentration of merging and diverging problems has been alleviated successfully; the long queue no longer exists. The control case also achieved smoother speed distribution that allowed smooth vehicle travel. In order to gain a better understanding, the auxiliary lane speed is recorded up to 120m upstream (on-ramp), while this distance in lane 3 is 500m.
Figure 9: Speed contour plot between base case and control case for auxiliary lane and lane 3


4.3.1.1 Impact of different OD matrices on the strategy

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

- 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 with five different OD as shown in Table 9. The five different tests result from a combination of one FF (5300 vph), one total weaving flow (1800 vph), one RR volume (100 vph) and five different RF ratios\(^2\). The level of service (LOS) in each of the scenarios is E, which is analysed based on HCM 2010, chapter 12 [13]. LOS E indicates that the network is heavily congested. Note that the HCM 2010 does not distinguish LOS with different RF ratios.

Table 9: Different OD matrices

<table>
<thead>
<tr>
<th>Test</th>
<th>RF (vph)</th>
<th>FR (vph)</th>
<th>FF (vph)</th>
<th>Total weaving (vph)</th>
<th>RR (vph)</th>
<th>RF ratio</th>
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<td></td>
<td></td>
<td></td>
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</tr>
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</table>

The bar chart in Figure 10 compares the average delay between the base case and the control case, while the line graph shows the delay improvements in terms of percentage with the different ODs.

---

\(^2\) Ramp to freeway (RF) ratio: the ratio between ramp to freeway and the total weaving flow.
Figure 10: Impact of different ODs on the strategy

The base case (blue column) shows that the weaving section has its minimum average delay when the RF ratio is at 0.5 with 9.4 (s/veh): that is, the two weaving flows (FR and RF) are equal. The value increases when either weaving flow (RF or FR) increases. This is because the one-sided ramp-weave requires a single lane change; a more balanced weaving distribution of the total weaving flow results in a better gap utilization [44].

On the other hand, the average delay time in the control case (red column) shows a different pattern. In fact, it reduces linearly as the RF ratio increases. The average delay in the control case, at RF 0.3, is highest with more than 8 seconds. This number reduces gradually until the FR ratio is at 0.6 and 0.7.

To explain these results, the actual NL of weaving vehicles in different segments of the control case are recorded as shown in Table 10.
Table 10: Actual number of lane changes in the weaving section, with different RF ratios

<table>
<thead>
<tr>
<th>RF ratio</th>
<th>Number of lane changes in weaving section</th>
</tr>
</thead>
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<tr>
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<tr>
<td>0.3</td>
<td>281</td>
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<tr>
<td>0.4</td>
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<td>0.6</td>
<td>175</td>
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<tr>
<td>0.7</td>
<td>155</td>
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</tbody>
</table>

The data in Table 10 demonstrate that the lane-change concentration was spread further downstream of the weaving section when the RF ratio increased. 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).

In addition, the average delay improvements in terms of the percentage of those OD (test 1 to test 5) are drawn from the difference in delay time between base case and control case. Figure 10 indicates that the average delay improvement increases as the RF ratio increases. The number stood at approximately 25% when the RF ratio was at 0.3 and achieved its peak at the RF ratio 0.7 with around 55%.

**4.3.1.2 Impact of different penetration rates on the strategy**

This section outlines how the strategy was influenced by different penetration rates. The rate of 5%, 10%, 20%, 40%, 60% and 80% were conducted.

Figure 11 shows the results with different penetration rates for RF ratios in terms of actual saving time, which expresses how many seconds that the strategy has saved.
Overall, increased penetration received more positive benefits, as expected. Even with the penetration rates as low as 5% or 10%, the strategy still achieved benefits. Compared with other studies, these results are quite remarkable. For example, a study by Park [38] shows that there is no significant improvement if the rate falls below 70%.

Again, the figures also increase as the RF ratio increases. RF ratio 0.7 always had the most benefits, except for its penetration rate low (<20%). With the expected travelled time (free flow speed) of ramp-vehicles and mainstream vehicles being 20.25 seconds and 32.40 seconds respectively, the maximum saved time, of more than 6 seconds in several cases, particularly in RF ratio 0.7, are noticeable.

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 instructions to 60% of the total vehicles, the predicted positive outcomes would be close to the fully connected scenario.
Table 11 shows the NL (%) in the weaving section with different penetration rates. Discussions are as follows:

- The percentage NL of FR vehicles in segment A are always higher than those of the RF. However, for segment B, the pattern is reversed vehicles in the same segment (i.e. percentage NL of RF vehicles are higher than those of FR vehicles), except for RF 0.7 at 100% penetration rate. This can most likely be attributed to the fact that diverging vehicles locate themselves into the auxiliary lane immediately after they approach the weaving section, whereas merging vehicles first enter the auxiliary lane, then travel a considerable distance before changing lane to the mainstream [21].

- It is clear that the differences in NL between the 100% and the 60% penetration rates are quite significant; however, the operational effectiveness measures, which are reflected in the actual saving time, are rather close to each other (shown in Figure 11). There are approximately 90% NL located in segment A and B in base case, while this number is about 50% at 60% penetration rate. This means that approximately 40% NL have shifted to segment C and D. One conclusion drawn from here is that if 40% of the NL located at the bottleneck shifts to the weaving section downstream (100m from the merge gore), the network almost achieves the majority operational benefits.

- The actual saving time of RF at 0.7 of the 80% penetration rate is a little higher than the one in the 100% penetration rate. This shows that the lane-change distribution values, as a result of the 80% penetration
rate at RF 0.7, provide a better outcome compared to that at the 100% penetration rate (even though the discrepancy is unimportant).
Table 11: Number of lane changes (%) in the weaving section with different penetration rates

<table>
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<tr>
<th>RF ratio</th>
<th>A</th>
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<th>C</th>
<th>D</th>
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**Base case**

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**Control case**

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</table>
Figure 12 depicts how the speed is scattered over the auxiliary lane, with different penetration rates. The 100% speed graph line has the flattest figure while the 60% penetration rate and the base case have a common pattern.

![Auxiliary lane speed with different penetration rates](image)

Figure 12: Auxiliary lane speed with different penetration rate (scenario 1)

### 4.3.2 Evaluation of scenarios 2 and 3

Figure 13 and Figure 14 illustrate the actual saving time of scenarios 2 and scenario 3 respectively. Overall, the pattern and the values are quite similar to those observed and discussed in scenario 1.
Figure 13: Actual saving time of scenario 2

Figure 14: Actual saving time of scenario 3
To provide a deeper understanding regarding the actual saving time across the three scenarios, comparison regarding the actual saving time between scenario 1-scenario 3 and scenario 2-scenario 3 were analysed as illustrated in Table 12 and Table 13 respectively.

The data in Table 12 shows a high variation and the results are mixed. Since scenario 1 and scenario 3 have different weaving lengths and weaving advisory proportions, it is difficult to identify which factor dominant the high variation in the data.

On the other hand, scenario 2 and scenario 3 (Table 13) have different weaving lengths, hence, the data are more consistent. Overall, compared with scenario 2, most of the cases in scenario 3 have an increase in saving time (except for some of the cases when the penetration rate is low (at 5%) of RF is at 0.3).

Table 12: Comparison of actual saving time between scenario 1 and scenario 3

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<th>Penetration rate (%)</th>
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<td>0.4</td>
<td>-85%</td>
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<td>-50%</td>
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<td>-57%</td>
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<tr>
<td>0.7</td>
<td>56%</td>
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</table>

Table 13: Comparison of actual saving time between scenario 2 and scenario 3

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<td>-37%</td>
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<td>0.7</td>
<td>39%</td>
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</table>
Figure 15 and Figure 16 show the distribution of speed in scenarios 1, 2 and 3. It is seen that the speed distributions are different due to the advisory proportion and the weaving lengths advisory. Another observation is that scenario 3 has the smoothest speed distribution over space, which is the objective of the lane-changing advisory. Hence, among these three scenarios, scenario 3 is the optimum case to deploy the strategy.

Figure 15: Auxiliary lane speed with different scenarios
Figure 16: Lane 3 speed with different scenarios

4.3.3 Impact of the strategy on different weaving geometries

This section outlines the results when applying the strategy to different weaving geometries. While scenarios 1, 2 and 3 possess a 400m weaving section, this section tests the application with a 600m weaving section.

The effectiveness of this scenario is illustrated in Figure 17. Again, in common with scenarios 1, 2 and 3, the actual saving time of scenario 4 is quite similar. Given the fact that the vehicles require longer to complete the 600m weaving section than to complete the 400m length, the 600m weaving section achieved a less positive impact compared with the 400m weaving section.
The speeds of the auxiliary and lane 3 in scenario 4 are shown in Figure 18 and Figure 19. Again, the control case obtained better speed distribution compared to the uncontrolled scenario.
4.4 Summary

The lane-changing advisory application based on C-ITS has been evaluated in this chapter. While non-weaving vehicles travel as normal, the mandatory lane changes of weaving vehicles are managed and cooperated.

The analysis revealed that the strategy has improved the network significantly. It also found that the lane-changing advisory proportion does not heavily influence the operation effectiveness between different scenarios; however, it may play an important role in having the smooth drive across the weaving section. The research findings are summarised in chapter 5.
Chapter 5: Conclusions

In this study, a lane-changing advisory in weaving sections based on C-ITS was proposed and evaluated. The research motivations build on two main reasons. 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 behaviour creates a bottleneck around the merge gore area, limiting weaving capacity, comfort and safety. Secondly, the advancement in wireless technology, as illustrated in the Cooperative Intelligent Transport Systems (C-ITS), brings an opportunity to alleviate the problem. Vehicles are able to exchange information with infrastructures and vice versa. That is, individual vehicles are monitored and advised through the personalized message based on their destination lane.

5.1 Research findings

Followings are the findings from the study, which answered the research questions outlined in Chapter 1.

- How can the C-ITS improve the utilization of current infrastructure by the infrastructure-to-vehicle communication?
  
  o The reality is that a significant proportion of weaving vehicles perform their lane changes close to the merge gore area. The infrastructures then communicate, sending advisory messages to the targeted groups of vehicles. The messages outline the location at which they should start to change lane in the weaving section. Hence, the concentration spreads out over the existing auxiliary lane and lane 3. By doing so, the lane-changing
activities are evenly distributed and the weaving section, especially at downstream, is fully used.

- **How is the C-ITS application influenced by penetration rates?**
  
  - The results evaluation has 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 is also found that the benefit of the 100% penetration rate is 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 the fully connected scenario.

- **At which traffic demand and condition does C-ITS provide the best measurement of effectiveness?**
  
  - Having the entire test scenarios classified as level of service (LOS) E suggests that the advisory strategy works well when traffic volume is close to the capacity. The bottleneck becomes more severe at 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.

- **What are the impacts of the proposed strategy on different weaving geometries?**

  - Two weaving lengths (400m and 600m) has been studied and evaluated. It is found that the actual saving time of these two weaving
lengths is rather similar. Given the fact that the 600m weaving section takes longer to complete, having similarity in the saving time means that the 400m weaving section has achieved a more positive outcome than that of the other.

5.2. Final discussions and recommendation for future works

It is clear that this C-ITS advisory application lies on several assumptions (Section 4.1.2), and field operational tests would provide the most reliable and accurate outcome. Nevertheless, this study is one of the first to investigate the benefits of C-ITS in the lane changing concentration in weaving sections by coordinating weaving vehicles.

- The penetration rate and the compliance rate (first and second assumptions) are related to each other, such that the two terms are interchangeable, and this study considers the penetration rate only. The result analysis indicates that if the infrastructure were able to connect and give instructions to 60% of the total vehicles, the obtained positive outcomes would be close to the fully connected scenario (or at the 100% compliance rate).

- By using the communication between vehicle and infrastructure (V2I) (third assumption), vehicles can forward their origin and destination lane to roadside units. In this way, the O-D in real time can be identified.

In short, when the infrastructure (roadside units) and the number of equipped vehicles are readily available, this strategy can be implemented in practice.
The author suggests a number of topics that can be considered as future work to make this research more comprehensive:

- Although the benefits at the 60% penetration rate is close to those at the 100% penetration rate, as shown in scenario 1, the aggregated speed reveals that the 100% case receives the smoothest drive. Further evaluation is recommended to look at this phenomenon, such as looking at the density for a better understanding.

- 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 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 results and conclusions derived from this study are clearly relative to the strengths and limitations of the AIMSUN software, and it is also assumed that AIMSUN correctly models driving behaviour. It should be noted that the proposed strategy was implemented using the Application Programming Interface (API) functions provided by AIMSUN. To apply a lane changing in the right way is important for the credibility of the simulation evaluation. According to Chapter 3, the proposed strategy only provides advice to certain
vehicles regarding where they should start perform their lane-changing, but
does not force any vehicles to change lane. In the developed API code, all the
lane-changings are still governed by the lane-changing model embedded in
AIMSUN. The developed API code only provides a reference point for C-ITS
enabled vehicles to undertake lane-changing. In order words, the comparison
between the base case and control case are based on the simple advisory
concept. 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.
References


