Calibration and Operational Analysis of Variable Speed Limits for High Flow Conditions

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Abstract—**Variable Speed Limits (VSL) is a control tool of Intelligent Transportation Systems (ITS) which can enhance traffic safety and which has the potential to contribute to traffic efficiency. This study presents the results of a calibration and operational analysis of a candidate VSL algorithm for high flow conditions on an urban motorway of Queensland, Australia. The analysis was done using a framework consisting of a microscopic simulation model combined with runtime API and a proposed efficiency index. The operational analysis includes impacts on speed-flow curve, travel time, speed deviation, fuel consumption and emission.**

I. Introduction

Variable Speed Limits (VSL) are a type of Intelligent Transportation System (ITS) that can utilize traffic detection, weather information and road surface condition technology to determine appropriate speed limits at which drivers should be travelling, given current roadway and traffic conditions. These regulatory speeds are usually displayed on overhead or portable variable message signs (VMS) [1]. Since the 1960s, trials of VSL have been taken place in countries including the US, the UK, Netherlands, Germany, Australia and New Zealand.

There are two main objectives for deploying VSL, improving safety and efficiency. VSL installations have significantly improved safety [2-5] due to the ability to reduce the potential for driver errors, excessive speeds and speed differentials between cars and lanes to create a more homogeneous traffic flow, which contributes to a safer motorway. However, there are no consistent results to support the claim that VSL substantially contributes to improved traffic efficiency [2, 4, 6-7]. Therefore, this study focuses on the use of micro-simulation when conducting calibration and evaluation to determine whether VSL can improve traffic efficiency.

There are limited studies in the literature that discuss the relationship between traffic condition changes and the speed limits displayed when using VSL. For example, which is better: to limit driver speed before congestion; display the average speed of the current traffic condition; or employ a speed limit that is higher than the average speed? This study also focuses on finding an optimal pattern of selection of displayed speed limits.

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In order to achieve these goals, the study calibrates and evaluates traffic flow impacts of a candidate VSL algorithm for high flow conditions on an urban motorway in Queensland, Australia. Compared with studies which propose and test VSL theoretically, this study investigates a candidate algorithm in the field, so practical considerations, including 1min-interval loop detector data and maximum speed limit reductions.

The paper is structured as follows. The target motorway network and its simulation model are described, and the candidate VSL algorithm - High Flow (HF) algorithm - and its integration in the simulation model are then introduced. Results and findings of calibration and operational analysis are reported, and conclusions are identified and summarized.

II. Description of Study Network

A. General Geometry

A 30-km section of the northbound Pacific Motorway (M3) which connects Logan city and the Brisbane CBD was selected as the study network (See Figure 1). The M3 services a large volume of commuter traffic in both morning and evening peak periods, leading to heavy recurrent congestion and a high frequency of incidents. For these reasons, local authorities consider the M3 as an ideal motorway to deploy VSL to alleviate serious congestion problems in southeast Queensland, Australia.

The M3 has five mainline lanes at its start and end, and mostly three mainline lanes in between. It experiences a volume of 130,000 vehicles daily. Installed on the motorway are 49 dual-loop detector stations in the northbound mainline, spaced approximately 650m apart, and single-loop stations on the on- and off-ramps. Speed, volume and occupancy are recorded every minute for all mainline stations, while volume and occupancy are recorded for all ramp stations. There are two default speed limits in the study network, 80 km/h for the sections near the Brisbane CBD and 100 km/h for other sections.

B. Simulation Model and Base Case

The preferred modeling platform in use is Aimsun 6.1. The Aimsun network for the M3 contains 48 sections and 15 on-ramps northbound. The network was edited by Queensland's Department of Transport and Main Roads, and model parameters calibrated by QUT's Smart Transport Research Centre. Once the demand scenario was prepared, the model was ready for testing.

A complete scenario to depict the real traffic demand on the network was developed in terms of traffic state according to the PTDS (Public Transport Data Source) database. The selected case day was 15th March 2010, this being a regular business day (Monday) with major educational institutions running, good weather prevailing (no rain) and no incidents reported. The complete scenario was conducted for a period of 17-hour with time intervals of 15 minutes. According to the whole day volume contour, the morning peak period was determined to be a 5-hour period from 5am to 10am when the northbound traffic experiences high levels of recurrent congestion. The base case for this study was the peak period demand without any traffic management (see the base case speed contour in Figure 2).

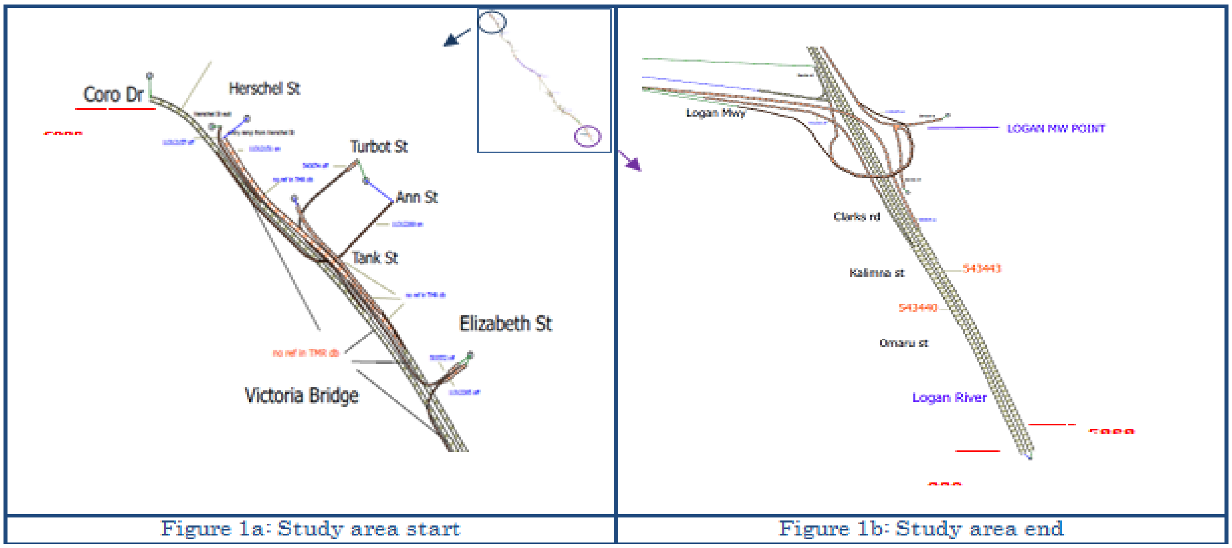

Fig. 1. Pacific Motorway.

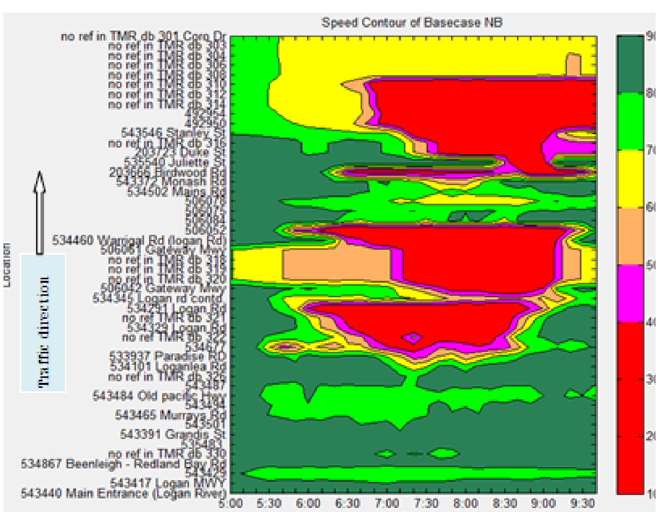

Fig. 2. Speed contour of the base case

III. HIGH FLOW ALGORITHM AND ITS API

The candidate VSL algorithm was written for high density and stable flow – High Flow (HF) algorithm [8]. The original aim of the HF algorithm was to delay the onset of flow breakdown and increase throughput.

A. Design Objective of HF Algorithm

When demand on a motorway section approaches capacity, the probability of flow breakdown increases. Under such conditions, flow breakdown is often triggered by traffic turbulence (for example, one vehicle braking to allow an aggressive driver to merge onto the motorway). Turbulence can be caused by:

1. Speed differentials between vehicles; and
2. Lane changing and merging.

By lowering the speed limit, the speed differentials between vehicles are expected to reduce, especially the speed differentials between different lanes, so the advantage of travelling in the fast lane is diminished. Consequently, lane utilization is more even and vehicles are less likely to change lanes for the purpose of overtaking. These behaviors were observed in London on the M25 [3].

According to the speed-flow curve (see Figure 3), lower speeds should result in a slightly higher stable volume before breakdown occurs. Obviously, lower speeds lead to higher density so it is possible to achieve higher sustainable throughput (volume) by slowing drivers in advance. In summary, the design objective of the HF algorithm is to use VSL to slow drivers in order to achieve speed harmonization as well as the delay of breakdown-onset.

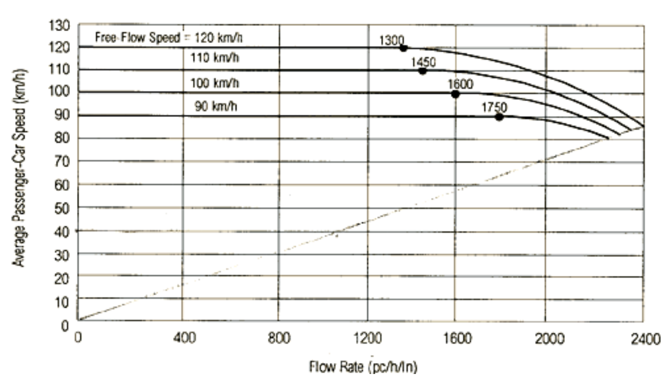

Fig. 3. Speed-flow curve [8]

B. *Basic Layout and Logic of HF Algorithm*

VSL installations are designed to be displayed on 42 gantries, spaced approximately 600-700m apart, in the northbound of the M3, with a detector station for each gantry. The area affected by each gantry starts at the point 70m in front of the gantry, and ends at the start point of the next gantry-affected area. Based on traffic data received every 1 minute from "Detector Station A", the HF algorithm is able to determine the appropriate speed limit to be displayed at "Gantry A", and this displayed speed limit therefore governs "Area A". This infrastructure layout is called gantry/DS/area group, and is illustrated in Figure 4.

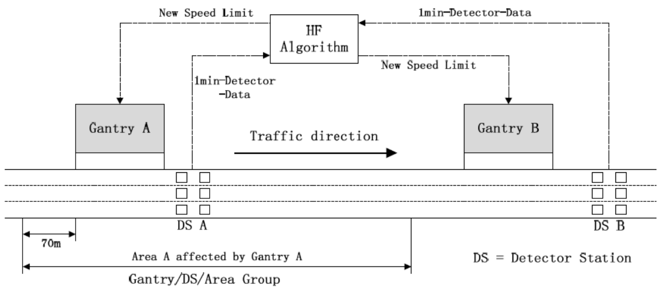

Fig. 4. Layout of gantry/DS/Area group

The HF algorithm is designed to select speed limits based on measures of average station volume or occupancy. The algorithm uses two sets of thresholds to determine the speed limits (See Figure 5). One set of thresholds is for the period when the volume is increasing, called increasing thresholds; the other set is for the period when the station volume is

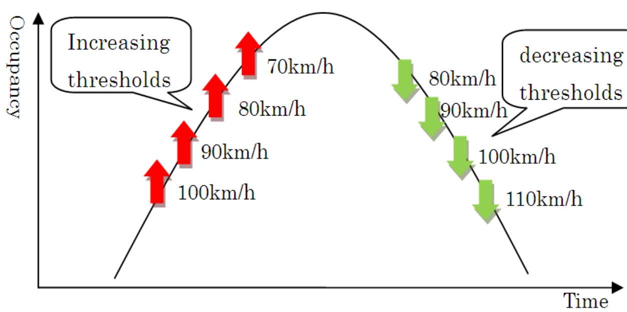

Fig. 5. Two threshold sets [8]

decreasing, called decreasing thresholds. The thresholds can be volume or occupancy. In this study, the occupancy thresholds are used because occupancy value is more stable than volume [9]. Therefore, for one gantry/DS/area group, the process of determining new speed limits is shown in Figure 6. The settling time check in Figure 6 means that after a reduction in the displayed speed limit has occurred, the speed limit cannot be increased until a pre-defined number of consecutive intervals of traffic flow improvement are detected; this pre-defined number of consecutive intervals is called settling time.

Once all the speed limits for gantry/DS/area group are determined, every upstream gantry must be guaranteed to obey the increment limit. Increment limit requires that the upstream gantry at any location must not display a speed limit which is greater than 10km/h higher than its downstream gantry. This provides a gradual transition for drivers. For instance, if the posted speed limit is reduced from 80 to 60 km/h at the response zone, then its upstream gantry should display no more than 70 km/h even if its new speed limit is over 70 km/h.

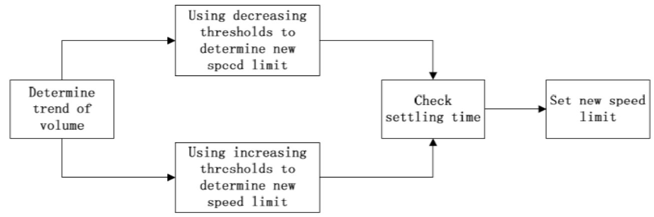

Fig. 6. Decision process for one gantry/DS/area group

C. *API Development of HF Algorithm in Aimsun*

The HF algorithm is interfaced with the simulator via the Aimsun API (Application Programming Interface) that allows reading of real-time simulation data, and the changing of some run-time parameters to achieve the control purpose for every simulation step. In the HF API, the gantry-affected area was coded as a series of segments that are grouped by the locations of gantries. Therefore, the process of API is firstly reading 1 minute aggregate data from the detector; the HF algorithm then calculates new speed limits and finally the speed limits of those segments are changed by the HF API.

IV. CALIBRATION METRICS – HF INDEX

In order to calibrate the thresholds of the HF algorithm, this paper proposes an HF index as the performance indicator. The HF index combines productivity and reliability of National Performance Indicators (NPIs) for network operations in Australia [10]. Both productivity and reliability are measures of network efficiency, so the HF index is focused on efficiency rather than safety. There are two reasons for this. First, it is already widely acknowledged that VSL can contribute significantly to safety improvements due to a more homogeneous traffic situation. This study therefore focuses solely on the efficiency performance of the HF algorithm. Secondly, it is difficult to measure safety impacts in a simulation environment.

NPIs are a set of measurements to evaluate network operations in Australia. In this study, productivity and reliability were chosen to form the HF index:

1. Productivity: this indicator is based on the product of speed and flow. A high productivity is achieved if both speed and flow are maintained near maximum values, i.e. near free-flow speed and capacity flow. The indicator is displayed as the proportion of a network at various levels of productivity in a measurement period. It is calculated as follows:

$$\text{Productivity} = \begin{cases} \dfrac{\text{speed}\times\text{flow}\times 100\%}{\text{speed}_{\text{nom}}\times\text{flow}_{\text{nom}}}, & \text{for speed} < \text{speed}_{\text{nom}} \\ 100, & \text{for speed} \geq \text{speed}_{\text{nom}} \end{cases} \quad (1)$$

where, $speed_{nom}$ is the normalization speed, 80km/h, and $flow_{nom}$ is the normalization flow rate, 2000 veh/h/l.

2. Reliability: this indicator measures the variability of speeds by calculating the coefficient of variation in a manner similar to the route variability of travel time. In order to align it with the productivity indicator trend, 1 minus the route variability of travel time as the reliability indicator is used. It is calculated as follows:

$$\text{Reliability} = 1 - \text{Route variability } VTT_h = 1 - 1.44 \times (\frac{SD_h}{T_h} \times 100\%) \quad (2)$$

where, T_h is the mean travel time on route h and SD_h is standard deviation of travel times on route h. The higher the reliability indicator is, the more reliable the level at which the network is running.

Productivity and reliability need to be normalized before calculation of the HF index:

$$x_{nom} = {(x - \bar{x})}/{\sigma} \quad (3)$$

where, $\bar{x}$ is the mean of the base case and σ is the standard deviation of the base case.

The HF index is calculated as follows:

$$\text{HF Index} = {}^{1}/_{2}\, \text{Productivity}_{nom} + {}^{1}/_{2}\, \text{Reliability}_{nom} \quad (4)$$

V. Calibration of Occupancy Thresholds

A. Critical Sections

The Pacific Motorway is a large network, so in order to determine the critical sections which should be focused on, the HF algorithm with initial occupancy thresholds is simulated and results analyzed. The speed contour for the initial occupancy thresholds is shown in Figure 7. Compared with the base case, the traffic situation from Murrays Road to Logan Road (12 sections in total) deteriorates (longer and expanded congestion) when the HF algorithm is activated. Therefore, the 12 sections between Murrays and Logan Roads (total length of 7.1km with 6 on-ramps and 4 off-ramps) are considered to be critical sections for the threshold calibration.

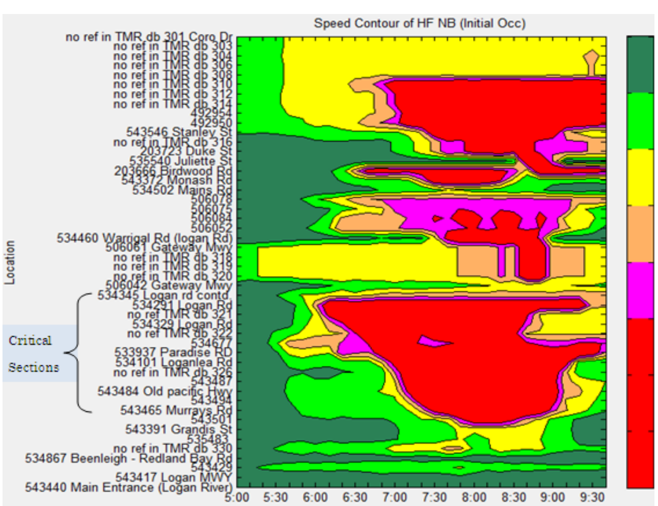

Fig. 7. Speed contour of HF algorithm with initial thresholds and the critical sections

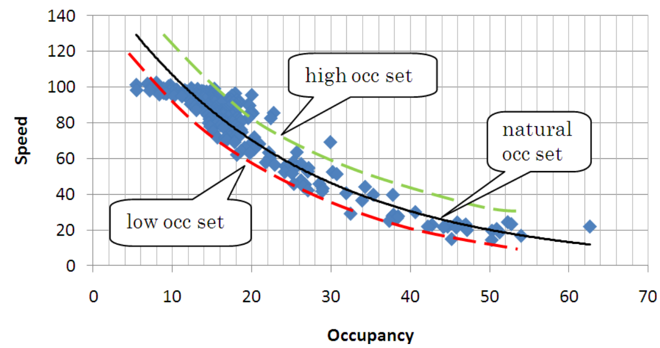

Fig. 8. Speed-occupancy curve

B. Candidate Threshold Combinations

The objective of this conceptual calibration is not to identify the optimal occupancy threshold value but to identify the pattern which will allow selection of an appropriate occupancy threshold. The first step in obtaining candidate threshold combinations is to analyze the occupancy-speed curves derived from real detector data. Two speed-occupancy curves from two different locations on the Pacific Motorway were analyzed (one example of the speed-occupancy curve is shown in Figure 8). The speed-occupancy curves identify three occupancy threshold combinations: low occupancy set, natural occupancy set and high occupancy set.

1. For the low occupancy set, the occupancy thresholds are determined by the points on the red curve in Figure 8. When the HF algorithm deploys this set, the HF algorithm slows drivers before the traffic condition gets worse. In other words, the displayed speed limit is reduced in advance.
2. For the natural occupancy set, the occupancy thresholds are the values on the black curve in Figure 8. In this configuration, the HF algorithm displays the average speed for current traffic conditions in the gantry-affected area as the speed limit.
3. For the high occupancy set, the occupancy thresholds are determined by the points on the green curve in Figure 8. In this instance, the HF algorithm actually reacts to the delayed traffic conditions.

C. Simulation Results

Four scenarios, including the base case and three candidate threshold combinations, were simulated to conduct the conceptual calibration. Each scenario was simulated five times and the average calculated in order to eliminate influences of random seeds in micro-simulation. The HF index for both the critical sections and the whole network was then calculated for all four scenarios. The results are listed in Table 1.

TABLE I
RESULTS OF HF INDEX

Scenario	HF index of critical sections	HF index of the whole network
Base case	0	0
Low occupancy set	-0.520	0.016
Natural occupancy set	-0.419	0.072
High occupancy set	-0.448	0.047

D. Optimal Pattern of HF Threshold Selection

The results of the HF index indicate that the natural occupancy set gives the best performance. This reveals the optimal pattern for HF threshold selection: to achieve the most suitable speed limits displayed, the best occupancy thresholds for one particular section should be determined by its speed-occupancy curve. Because the speed-occupancy curve is retrieved from statistical data for the section, the speed is the most stable value for the corresponding occupancy.

This result leads to both positive and negative implications for the VSL installation. On one hand, it is promising in terms of engineering practice. The VSL algorithm only requires drivers to keep to the speed which is suitable for the prevailing traffic conditions, so it is easy for drivers to understand and to follow the new speed limits. This high level of driver acceptance will ensure the design objective of VSL is easier to achieve. However, it might indicate, on the other hand, that VSL is not a good choice for improving traffic efficiency. When slowing drivers in advance, the efficiency indicator - the HF index - becomes worse than the base case. In this case, the appropriate design objective for VSL is speed harmonization only not efficiency improvement.

VI. OPERATIONAL ANALYSIS OF HF IMPACTS

In this section, analyses are made by comparing the base case and the HF algorithm with the natural occupancy set. Firstly, the overall operation comparison is made, and then a theoretical analysis of the impacts on speed-flow relationship is conducted. Thirdly, the results of a comprehensive operational analysis are discussed. Finally, suitable conditions for the HF algorithm are identified.

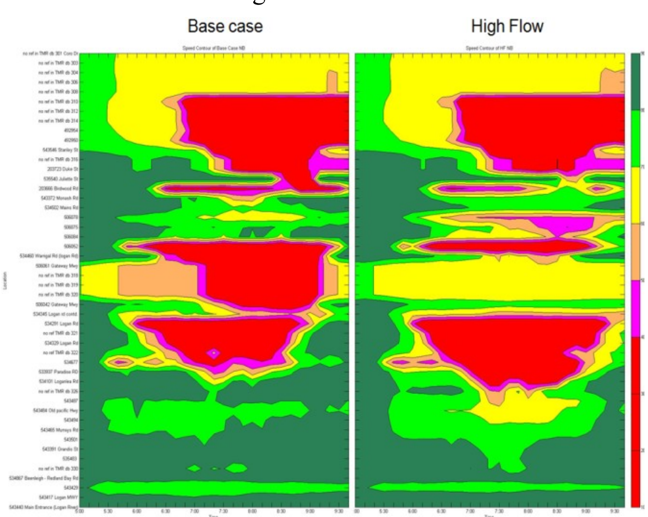

Fig. 9. Speed contour comparison of base case and HF algorithm with natural occupancy set

A. Overall Operation Evaluation

Speed contour is the best way to check when and where the traffic flow breakdown occurs, and is relieved. Therefore, overall operation evaluation checks the speed contours before and after activation of the HF algorithm (see Figure 9).

For the critical sections identified in the former section, the HF algorithm makes the traffic conditions worse: the flow breakdown starts earlier and spills back to upstream, and then delays the recovery. In this area, there are 6 on-ramps and 4 off-ramps with high demands, so a large number of lane-changing and merging are necessary. When the HF algorithm is activated, lower speed limits increase traffic density which makes it difficult for lane-changing and merging. Consequently, congestion even starts earlier and propagates back into the upstream.

For the four sections just downstream of the critical sections, the HF algorithm eliminates the flow breakdown. This is mainly due to the more serious congestion occurring at the critical sections upstream, which reduces the mainline volume of these sections where no ramp exists. This could be evidence that the HF algorithm can contribute to improved efficiency.

For rest of the network, the HF algorithm does not have a significant influence.

B. Impacts on Speed-Flow Curve

This section analyzes the influence of the HF algorithm on the speed-flow relationship around the whole network. Eight pairs of speed-flow curves (all eight sections experience congestion during the simulation period: four are from critical sections and four are not.) are analyzed; one pair for one section includes the speed-flow curves before and after the HF algorithm is activated.

An example of the speed-flow curves is given in Figure 10, demonstrating two similar patterns for the change before and after the HF algorithm is activated.

1. The speed after the HF algorithm is activated is slightly lower than the speed before (around 5 km/h) when dots are in the red rectangle. This is expected to happen with the HF algorithm.
2. The dot-density after the HF algorithm is activated is higher than its counterpart before in the red rectangle, and the opposite situation in the green rectangle. This implies that the traffic is more stable with the HF algorithm.

C. Comprehensive Operational Analysis

This section lists results of a comprehensive operational analysis, including travel time, speed deviation, fuel consumption and emission. The results are shown in Table 2.

The travel time impacts of the HF algorithm are calculated for both critical sections and the whole network. For the critical sections, the average travel time increases significantly (31.03%). This large increase is due to the longer congestion caused by the HF algorithm in these sections. For the whole network, the normalized travel time is almost the same.

The speed deviation impacts are calculated for critical sections. For the critical sections, there is a large decrease in speed deviation (11.39%) which implies good speed harmonization in this area. This is indirect evidence that the HF algorithm can contribute to improved safety.

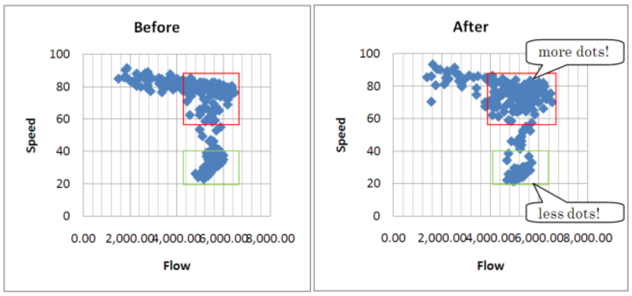

Fig. 10. Speed-flow curves before and after activation of the HF algorithm

The fuel consumption and emission impacts are calculated for the whole network. Both fuel consumption and CO2 emission significantly decrease. The HF algorithm results in more harmonized traffic flow which has the potential to reduce accelerations and decelerations, thereby creating more eco-friendly driving.

TABLE II
RESULTS OF OPERATIONAL IMPACT ANALYSIS

	Base case	HF with natural occupancy set	Change
Travel Time of Critical Sections	57.11s	74.83s	31.03%
Travel Time of Whole Network	71.06s/km	70.77s/km	-0.41%
Speed Deviation of Critical Sections	7.46km/h	6.61km/h	-11.39%
Fuel Consumption*	98803L	90812L	-8.08%
Emission of CO2*	230073kg	222050kg	-3.49%

* The fuel consumption and emission models used in this study were those embedded in AIMSUN 6.1.

D. *Suitable Conditions for the HF algorithm*

According to the results from speed-flow curve analysis, the HF algorithm is able to achieve speed harmonization and better environmental impacts. However, it exacerbates congestion even more serious for the section with high ramp-density and large ramp flows (such as critical sections). Therefore, the HF algorithm is suitable for those motorway sections which have low ramp-density or where the ramp flows are small.

VII. Conclusions

This study describes the design of a calibration and evaluation framework for a candidate VSL algorithm, the HF algorithm, for a congested Australia motorway. The framework consists of a microscopic simulation model combined with runtime API and a HF index. The HF index was designed to reflect network efficiency rather than safety by combining productivity and reliability of NPIs for network operations in Australia.

This study proposes an optimal pattern for HF threshold selection: to achieve the most suitable speed limits displayed, the best occupancy thresholds for one particular section should be determined by its speed-occupancy curve. This also describes the relationship between traffic condition changes and the displayed speed limits.

The operational analysis gives inconsistent results on efficiency indicators (opposite results for critical sections and the whole network in terms of the HF index, travel time). The reasons for these inconsistent results need further investigation. However, the results provide evidence of VSL's positive impact on the environment.

Acknowledgment

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