Australasian Transport Research Forum 2013 Proceedings
2 - 4 October 2013, Brisbane, Australia
Publication website: http://www.patrec.org/atrf.aspx

A Multi-hierarchical Motorway Ramp Signalling Strategy

Rui Jiang[1], Jinwoo (Brian) Lee[2], Edward Chung[1]

[1] Smart Transport Research Centre, Civil Engineering and Built Environment School, Science and Engineering Faculty, Queensland University of Technology, 2 George Street, QLD 4001, Australia

[2] Civil Engineering and Built Environment School, Science and Engineering Faculty, Queensland University of Technology, 2 George Street, QLD 4001, Australia

Email for correspondence: r1.jiang@qut.edu.au

Abstract

Ramp signalling is an access control for motorways, in which a traffic signal is placed at on-ramps to regulate the rate of vehicles entering the motorway and thus to preserve the motorway capacity. In general, ramp signalling algorithms fall into two categories: local control and coordinated control by their effective scope. Coordinated ramp signalling strategies make use of measurements from the entire motorway network to operate individual ramp signals for the optimal performances at the network level. This study proposes a multi-hierarchical strategy for coordinated ramp signalling. The strategy is structured in two layers. At the higher layer with a longer update interval, coordination group is assembled and disassembled based on the location of high-risk breakdown flow. At the lower layer with a shorter update interval, individual ramps are hired to serve the coordination and are also released based on the prevailing congestion level on the ramp. This strategy is modelled and applied to the northbound Pacific Motorway micro-simulation platform (AIMSUN). The simulation results show an effective congestion mitigation of the proposed strategy.

1. Introduction

Ramp signalling (ramp metering) system uses a traffic signal at an on-ramp to regulate vehicles entering the motorway. Without ramp signal, high ramp flows merging into the motorway mainline increase the chance of flow breakdown and significant capacity reduction as a result. Ramp traffic also takes advantage of ramp signalling, because the congestion in the mainline eventually reduces the opportunity of ramp traffic to use the motorway.

Ramp signalling is considered to be the most effective tool currently available for motorway congestion, with its effectiveness already proven by field implementation results (Papageorgiou & Kotsialos, 2002). Particularly in Australia, ramp signalling has received increasing attention in recent years, as motorways in capital cities are suffering from heavily recurrent congestion caused by extended peak periods. Melbourne (Papamichail, Papageorgiou, Vong, & Gaffney, 2010) has already applied ramp signalling system on Monash motorway, and Brisbane has also commenced field tests.

In general, ramp signalling algorithms fall into two categories according to their effective scope: local control and coordinated control. The localised controller determines the metering rate based only on the local traffic conditions. This type of ramp signalling has some limitations. The most significant disadvantage is the inefficiency in utilising ramps as queue storage, causing unevenly distributed ramp queues along the network.

In order to tackle the aforementioned limitation, coordinated ramp signalling has been proposed since the 1980s (Jacobson, Henry, & Mehyar, 1989). Coordinated ramp signalling strategies make use of measurements from the entire motorway network to control ramp signals for the optimal performances at the network level. The availability of system-wide information enables operating ramp signals to achieve an enhanced efficiency of the whole motorway network and evenly distributed ramp utilisation and ramp queues. Therefore, coordinated ramp signalling represents the latest trend in the practice. Accordingly, this study focuses on developing a coordinated ramp signalling strategy for field implementation, which can overcome the limitations of local control and achieve the network-wide benefit of ramp signalling. Complex mathematical models and optimisation approaches require comprehensive and highly reliable traffic detector data, which is often implausible in reality. The new strategy takes the rule-based heuristic framework with the feedback concept embedded in the control structure. The proposed control approach is simple, transparent and less data-dependent.

The remainder of this paper is structured as follows. Section 2 briefly reviews two typical ramp metering control approaches: model-based and heuristic rule-based. In the following section, the problem of coordinated ramp signalling is stated. In Section 4, the new coordinated algorithm with the fundamental control concepts and components are introduced. The simulation evaluation results are presented in Section 5. Section 6 concludes this study.

2. Review of Existing Coordinated Ramp Signalling

Coordinated ramp signalling studies have been undertaken extensively over the last three decades. According to the methods of determining the coordination among ramp signals, coordinated ramp signalling strategies can be divided into two categories: the model-based optimisation method and the rule-based heuristic method.

2.1 Model-based optimisation Method

This type of algorithm attempts to optimise the metering rates of the ramps over an optimisation horizon. The algorithms in this category typically employ a macroscopic traffic flow model to estimate the current and the near future traffic conditions. From the control point of view, the ramp metering control is seen as a system optimal problem in this approach and the overall motorway network is described in a state-space form:

$$x(k+1) = f[x(k), u(k), d(k)] \tag{1}$$

where $x(k)$ is the network state vector, including occupancy, mean speed and queue length;

$u(k)$ is the control input vector, including the metering rates of metered on-ramp;

$d(k)$ is the external disturbance vector which is usually the traffic demand.

Typical control objectives adopted for optimisation are total vehicle travel time or total vehicle delay time, while field constraints can serve as penalty term in the objective function. For numerical optimisation, optimisation techniques such as linear quadratic programming or nonlinear programming are used. Examples of this control approach include the Linear Programming algorithm (Yoshino, Sasaki, & Hasegawa, 1995), and the Advanced Motorway Optimal Control (Kotsialos, Papageorgiou, Mangeas, & Haj-Salem, 2002).

Although this type of coordinated algorithm attempts to achieve the optimal traffic condition over the entire motorway network, application to the field is often impractical because network-wide traffic information, even short-time prediction, is required in real-time for the optimisation. This problem could be addressed by substituting measurements with estimates and predicts, but the accuracy of the traffic flow model using the estimated measurements as the input data is questionable.

2.2 Rule-based Heuristic Method

This type of coordination algorithm decides metering rates for participating on-ramps by a serious of pre-defined rules. Rules here are typically based on simple principles or extracted from historical analysis and expert experiences. For example, the demand-capacity principle has been used in many coordinated ramp signalling algorithms. This method requires the total traffic demand for a bottleneck (including the mainstream and on-ramp flows) must be known and the traffic demands that exceed the capacity would activate the coordination.

Another example is the Fuzzy logic technique based algorithm by Bogenberger and Vukanovic (2002). According to historical data analysis and expert experience, this algorithm generates several traffic patterns for the system-wide network and also for each on-ramp and pre-defines a metering rate for each metered on-ramp of each defined pattern.

The major advantage of the heuristic control approach is its good applicability and thus most of the field implemented coordinated systems fall into this category, such as the Helper ramp algorithm(Lipp, Corcoran, & Hickman, 1991), the Sperry algorithm (Virginia Department of Transportation, 1998) and the HERO algorithm (Papamichail, et al., 2010). However, simple rules are always of feed-forward nature, which cannot accurately describe complicated traffic conditions, especially critical traffic conditions. For example, computing metering rate based on the demand-capacity principle requires capacity as an input data, which is widely acknowledged as having stochastic nature. Using a fixed capacity setting always causes mismatch between the control model and the prevailing traffic condition. From this point of view, additional mechanisms should be introduced to make the algorithm more stable and to reflect the actual traffic conditions in the metered ramps.

3. Problem Statement

The main reason for requiring ramp coordination is the unbalanced traffic distribution along motorway networks. Specifically, traffic is unevenly distributed along the whole network. Heavy ramp flows and lane reductions are the main cause of recurrent congestion of the motorway network. With only local control, it is impossible to handle those on-ramps with heavy traffic flow due to queue constraints. As a result, traffic queues developed in those areas propagate upstream, activating other bottlenecks. In addition, only the on-ramps located close to the bottleneck would take action restricting the mainline access, given that localised ramp signalling is operated independently. Meanwhile, upstream ramps are not efficiently utilised because they would not detect congestion from their local information. To sum up, ramp coordination is required for better utilisation of network resources for congestion management.

According to the above analysis, ramp coordination is materialised by requiring upstream spare ramps to help the downstream critical ramp (an active bottleneck). Note that, traffic conditions, at the downstream bottleneck, cannot be affected by upstream ramps due to the distance between upstream ramps and downstream bottleneck. In other words, there is a time lag between upstream contributors (upstream ramps in coordination) and the downstream receiver (the bottleneck). A relatively long interval, covering the time lag, is necessary when considering coordination between ramps. With the long interval, the impact of coordination control executed in a previous interval can be measured by detectors at the downstream bottleneck. Accordingly, a new control decision can be made based on those detector measurements. However, a relatively long interval slows down the reaction speed of the control due to the high dynamics of traffic flow. For example, large incoming platoon can suddenly disable one ramp from participating coordination, and can even make the ramp become an active bottleneck. Considering the high fluctuation of traffic flow requires a short interval to enable quick response of the coordination to traffic conditions. Apparently, this is an issue of coordination caused by the time lag.

In addition, the objective of coordinated ramp signalling is to prevent congestion or to delay congestion. This requires the coordination control to be proactive: that is, to plan in advance. Considering the time lag, the coordination control should be even more proactive. An proactive control would involve prediction, but no prediction can guarantee absolute accuracy; therefore, the proactive control would introduce some errors and mismatches to reality. The reactive control can adjust the prediction errors and mismatches so as to improve the robustness of the coordination. Consequently, a coordination strategy needs to combine the advantage of proactive control and reactive control.

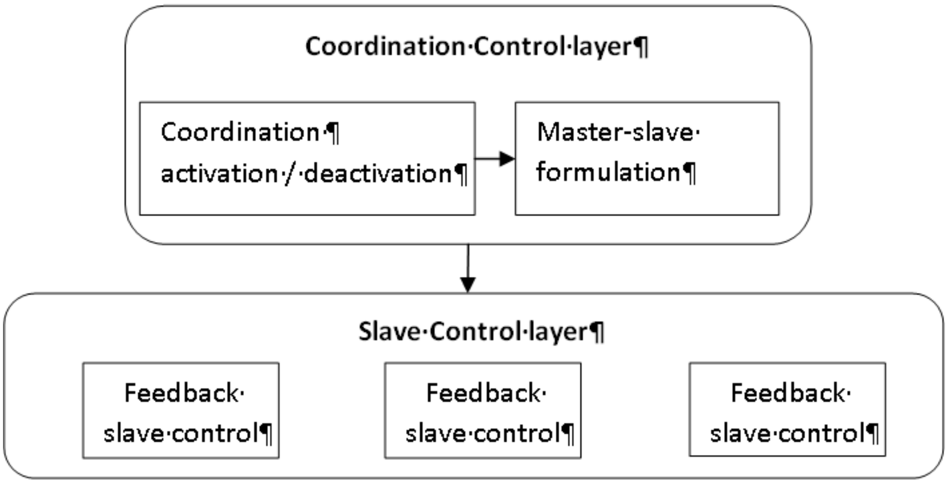
In summary, the purpose of this paper is to present coordinated ramp signalling strategy, combining proactive and reactive control, to overcome the time lag and to provide quick response to traffic conditions.

4. Strategy Development

4.1 Framework

As noted, this paper proposes a multi-hierarchical control framework (see Figure 1): a. both to cover the time lag and to provide quick reaction; b. to combine and take advantages of both the proactive and reactive approaches.

Figure 1: Multi-hierarchical control framework



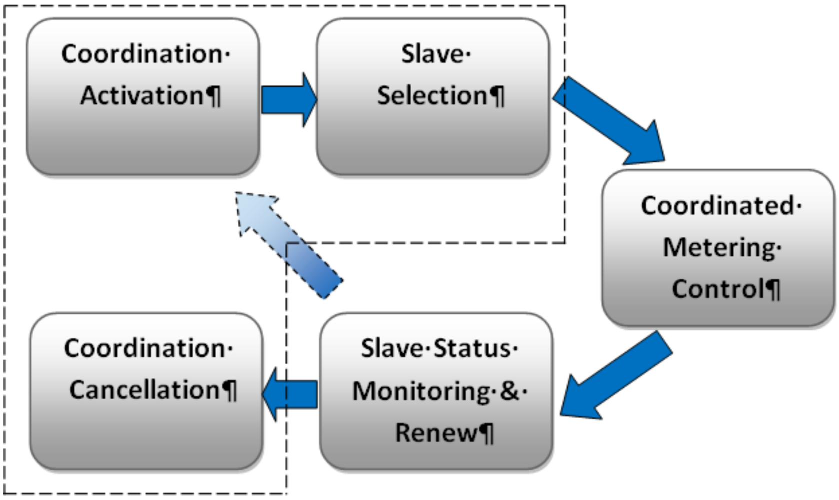
The higher level layer (or coordination control layer) is a centralised, predictive controller that plans the coordination control within a longer update interval. This is because planning the coordination affects a large part of motorway network (could be up to about a 10-km section). Also, the long update interval, covering the time lag, enables the updated plan being reactive to the coordination operation in the previous interval. In addition, the coordination is planned proactively with predictive information. One task undertaken at this layer is to activate coordination when the traffic measurements indicate an imminent flow breakdown in the near future. Another task is to dynamically define the coordination group based on the prevailing traffic condition at active bottlenecks.

The lower level layer (or slave control layer) incorporates reactive controllers that determine the metering rates of those ramps in the coordination group. In order to better overcome the time lag, a PID feedback controller is formulated and tested (see details in Section 4.3). The slave metering rate is calculated based on both the traffic density (loop detector occupancy) level in the downstream bottleneck area and its own ramp queue size. The control mechanism is a feedback approach that adjusts the slave metering rate continuously to achieve the desired traffic condition in the downstream bottleneck area. Compared with the coordination control layer, this layer considers both the actual changes at the downstream bottleneck and the slave's own condition, so a shorter update interval is adopted to enable quick feedback reaction on time.

4.2 Flowchart

The coordination strategy consists of five components as displayed in Figure 2; the flowchart of control is also presented. The first step is to identify the ramp(s) in need of coordination. A ramp with the queue size exceeding a certain threshold becomes a "master" ramp that requests coordination. The slave selection component recruits one or more upstream ramps as "slaves", switching their metering to the coordinated mode. The coordination group can be resized on a regular basis. A congested slave ramp will be released from the coordination. A new slave ramp could be recruited to replace the released one or to give additional aid to the master ramp. The last component cancels the coordination when the queue size in the master ramp reduces under a pre-specified level or all the available ramps are used up.

Figure 2: Flowchart of the coordination strategy



The three components in the dashed line area work at the coordination control layer, while the other two are at the slave control layer. The rest of this sub-section introduces four components: the coordination activation, the slave selection, the slave status monitoring & renew and the coordination cancellation. The coordinated metering control is introduced in Section 4.3.

4.2.1 Coordination Activation

This component identifies a master ramp and activates coordination. Three conditions would activate coordination: 1) a mainstream traffic state approaching the merging area capacity; 2) a ramp queue size exceeding a threshold level; and, 3) a ramp queue size projected to spill-over in the near future. The mainstream traffic state is measured and projected using the single exponential smoothing technique. The ramp queue size can be estimated using the on-ramp queue estimation algorithm presented in the literature (Lee, Jiang, & Chung, 2013). The aforementioned three conditions to activate coordination can be formulated as follows. Note that all the three conditions must be satisfied.

$$\begin{cases} Occ_i^{sm}(t) > Occ_i^{th} \\ NV_i^{est}(t) > NV_i^{th1} \\ NV_i^{prj}(t) > NV_i^{th2} \end{cases} \quad (2)$$

where *Occ* is detector occupancy;

i is the ramp index starting from the most upstream one to downstream;

"*sm*" indicates a smoothed value;

"*th*" indicates a threshold value;

"*est*" indicates a estimated value;

"*prj*" indicates a projected value; and,

NV is the queue length in ramp in terms of the number of vehicles.

4.2.2 Slave Selection

The process of slave selection is to seek sufficient assistance from slave ramps for the master ramp. The first step is to estimate the level of assistance required. The next step is to calculate the possible contribution from upstream ramps. The contribution is calculated for each ramp starting from the immediate upstream ramp of the master ramp until the sum of contributions exceeds the master requirement. Both the requirement and the contribution are calculated based on the projection of ramp flow (Chung, Lee, & Jiang, 2012).

4.2.3 Slave Status Monitoring and Renew

Although the decision to recruit a slave ramp is made based on the projected queue size, the queue projection is always subject to a forecasting error, so it is possible to create unacceptably long queues in the slave ramp. Once a slave ramp encounters its own queue problem, it must be released from the coordination and the mode of operation must also switch back to the normal local RM mode. In order to prevent those released ramps from taking benefit from other slaves located upstream, the module sets the maximum metering rate with the arrival flow rate. When one or more slave ramps are released from coordination, the module will search and recruit additional ramps to replace those released.

4.2.4 Coordination Cancellation

The coordination control might be cancelled by two conditions. One is that the master ramp is no longer in need of coordination because of enhanced traffic flow conditions. The other condition is that the master merging area falls into congestion so coordination is no longer an effective prevention measure. Either of these two conditions may cancel the coordination control and restore the local ramp signalling. These conditions can be formulated as follows:

$$\begin{gathered} NV_i^{est}(t) < NV_i^{thd}, Occ_i^{sm}(t) < Occ_i^{thd} \\ or \\ Occ_i^{sm}(t) \gg Occ_i^{tha} \end{gathered} \tag{3}$$

where NV_i^{thd} is the deactivation queue length threshold;

Occ_i^{thd} is the deactivation merge occupancy threshold;

Occ_i^{tha} is the activation merge occupancy threshold.

4.3 Coordinated Metering Control

This module controls the metering rate of all the metered ramps in the coordination group. This is a feedback controller and two strategies are included for master and slave ramps.

In the coordination mode, the master ramp will keep the local metering rate. The slave metering control will be determined by a PID controller.

PID controller is the most widely and successfully used controller type due to its simple and transparent form. The fundamental concept of the slave metering control is to let slaves react to the master ramp's traffic condition using the PID controller. The physical meaning of proportional, integral and derivative terms are as follows:

- P-term: the character 'P' stands for "proportional" and the P-term is designed to react for the instant error between target value and instant measurement. Consequently, it is calculated as the change of the accumulative error at interval t.
- I-term: 'I' means "integral", which indicates that the I-term reacts to the accumulative error at current interval.

- D-term: 'D' equals "derivative". Accordingly, the D-term represents the trend of the instant error, and in discrete form it is calculated as the change of the accumulative error change.

A standard discrete PID controller is given as follows:

$$\mathrm{r(t) = r(t-1) + K_P \cdot [e(t) - e(t-1)] + K_I \cdot e(t) +}\\ \mathrm{K_D \cdot [[e(t) - e(t-1)] - [e(t-1) - e(t-2)]]} \tag{4}$$

where r represents metering rate;

K_P, K_I, K_D are the coefficients for P-, I- and D-term; and,

e represents the error between measurement and desired value, given by:

$$\mathrm{e(t) = Occ^* - Occ(t)} \tag{5}$$

where Occ^* is the pre-defined desired occupancy for the controller; and,

$Occ(t)$ is the occupancy measurement at interval t.

Noted that the detector occupancy is an aggregated measurement, so the error, e(t), calculated in the above equation is the accumulative error during interval t.

Finally, the more restrictive metering rate between the local signalling algorithm (Jiang, Chung, & Lee, 2012) and the PID controller is selected for implementation. Accordingly, the slave metering control can be formulated as follows:

$$\begin{cases} r^C = PID(Occ^M) \\ r = min(r^C, r^L) \end{cases} \tag{6}$$

where r^C is the coordinated metering rate;

PID() is the PID based slave controller;

Occ^M represents the measurements from master merge area;

r^L is the local metering rate; and,

r is the final metering rate to implement.

5. Simulation Evaluation

5.1 Test-bed

The modelling platform used in the investigation is AIMSUN 6.1. The Pacific Motorway test-bed model was used for this research. The test-bed network is approximately a 30-km section of the northbound (inbound) Pacific Motorway (M3) from Logan City to the Brisbane CBD. There are 16 on-ramps and 17 off-ramps along the network. The traffic volume is about 130,000 vehicles per day. This motorway section serves a large volume of commuter traffic in the morning peak hours, leading to heavy recurrent congestion. For these reasons, local authorities consider the M3 to be an ideal motorway to deploy RM to improve efficiency.

The simulation network used in this study was edited by Queensland Dept. of Transport & Main Roads, and model parameters calibrated by Smart Transport Research Centre (Chung, Rahman, Bevrani, & Jiang, 2011). A complete scenario to depict the real traffic demand on the network was developed in terms of traffic state according to PTDS (Public Transport Data Source) database. According to the whole day volume contour, the morning peak period was determined as a 5-hour period from 5am to 10am, when the northbound (inbound) motorway witnessed high levels of recurrent congestion.

A total of three test scenarios were modelled in the AIMSUN simulation network for evaluation of the coordinated ramp signalling algorithm:

- Base case scenario assumes no RM control;
- Local ramp signalling (LRS) scenario operates a local RM control for all 16 on-ramps along the northbound Pacific Motorway;
- Coordinated ramp signalling (CRS) scenario operates the coordinated RM control upon an activation of coordination. Otherwise, ramps will operate local RM.

5.2 Performance Indicator

Four performance indicators are used to demonstrate the benefits and costs of the coordinated ramp signalling, compared with the local ramp signalling:

- Total Travel Time (TTT): the most widely used efficiency indicator at a system level for RM. It is calculated by summing up all the individual vehicle travel times in the network. The unit of TTT is veh·h.
- Average mainline traffic delay (MTD): this indicator gives a sense of the coordination benefit. The northbound Pacific Motorway is divided into 31 sections based on the location of metered ramps. For each section, individual vehicle travel time within the section is collected and aggregated into the average section travel time. The sum of average section travel times is the entire motorway travel time. The free flow travel time for the entire motorway is also calculated assuming 80 km/h as the free flow speed. Finally, MTD is defined as the difference between the actual mainline traffic travel time and the free flow travel time. The unit of this indicator is sec/trip.
- Total queue spillover time (TQST): the sum of the total time for each on-ramp when ramp queue spills over to upstream arterials. In this study, the queue spillover is defined as 1-min time occupancy of the ramp entrance detector is over 70%.
- Average ramp traffic delay (RTD): the way to calculate RTD is slightly different from MTD. Firstly, the aggregated travel time for each ramp is calculated by collecting individual vehicle travel times in ramp. The ramp travel time is collected from the ramp entrance to the downstream merge area. The free flow speed for this section is assumed at 70 km/h. The delay for each ramp is defined as the difference between the actual ramp travel time and the free flow travel time. To consider that the ramp traffic volume varies by each location, the average RTD is calculated using the following equation. The unit of this indicator is sec/veh.

$$RTD = {\sum_i RTD_i \cdot Q_i}\Big/{\sum_i Q_i} \qquad (7)$$

where RTD_i is the ramp traffic delay for ramp i; and,

Q_i is the total volume of ramp i.

5.3 Result and Analysis

In Table 1, the simulation results are summarised in terms of those four performance indicators from 15 simulated replications of each scenario. The base case scenario results the worst overall traffic condition, the highest TTT of 14221.8 veh·h and the highest MTD of 911.6 sec/trip. However, the ramp costs are the smallest, including the lowest RTD of 59.6 sec/veh and the shortest TQST of 220.4 minutes.

Installation of the LRS system made significant improvements to the overall traffic performance and the mainstream traffic. The TTT and the MTD decreased, with the LRS, by 19.9% (from 14221.8 to 11396.6 veh·h) and 53.1% (from 911.6 to 427.7 sec/trip). The LRS, however, negatively affects the TQST and the RTD.

Table 1: Coordinated ramp signalling evaluation results summary

	Unit	Base case	LRS	CRS
TTT	veh·h	14221.8	11396.6	11285.7
MTD	sec/trip	911.6	427.7	408.1
TQST	minute	220.4	620.1	624.9
RTD	sec/veh	59.6	133.8	153

Comparison of the LRS and the CRS clearly shows that the coordination control makes the mainstream flow much more quickly. The MTD decreases with the CRS by 4.6% over the LRS. The coordinated control also improved the overall traffic condition. The TTT is 11285.7 veh·h, which is a 1% reduction over the LRS and 20.7% reduction over the base case scenario. This is majorly because the most serious mainline congestion during the morning peak hours is caused by the Gateway Motorway interchange off-ramp, a weaving bottleneck rather than a merging bottleneck; so, it is not be the best test-bed for testing ramp signalling. Besides, the RTD increases by 14.3% with the coordinated control. Restricting the mainline access at additional metered ramps is a trade-off. It is noteworthy that the total queue spillover time increases only marginally, by 0.8%. This implies that the coordination strategy can efficiently utilise the queue storage of the slave ramps without causing excessive delays or long queues in those ramps; this also indicates that the strategy responses to traffic conditions quickly.

The macroscopic fundamental diagram (MFD) was first proposed by Daganzo (2005, 2007), who recognised that traffic in a large network can be modelled dynamically at an aggregated level. Geroliminis and Daganzo (2008) verified the existence of MFD using Yokohama data, and Geroliminis and Sun (2011) analysed the MFD for motorway networks. Although real data analysis showed that MFD in motorway networks is of high scatter and exhibits hysteresis phenomena, MFD is able to evaluate motorway traffic conditions at a system level.

In this analysis, the flow rate and density are aggregated for every 5 minutes, and the mainline MFD is defined as the weighted average flow rate against the average density of the mainline sections, based on the simulation data:

$$\bar{q}^w = \sum_i q_i \cdot l_i \Big/ \sum_i l_i \tag{8}$$

$$\bar{k} = \sum_i k_i \Big/ \sum_i 1 \tag{9}$$

where subscript “i” represents the section index;

$\bar{q}^w$ is the weighted average flow rate of the network;

q is section flow rate;

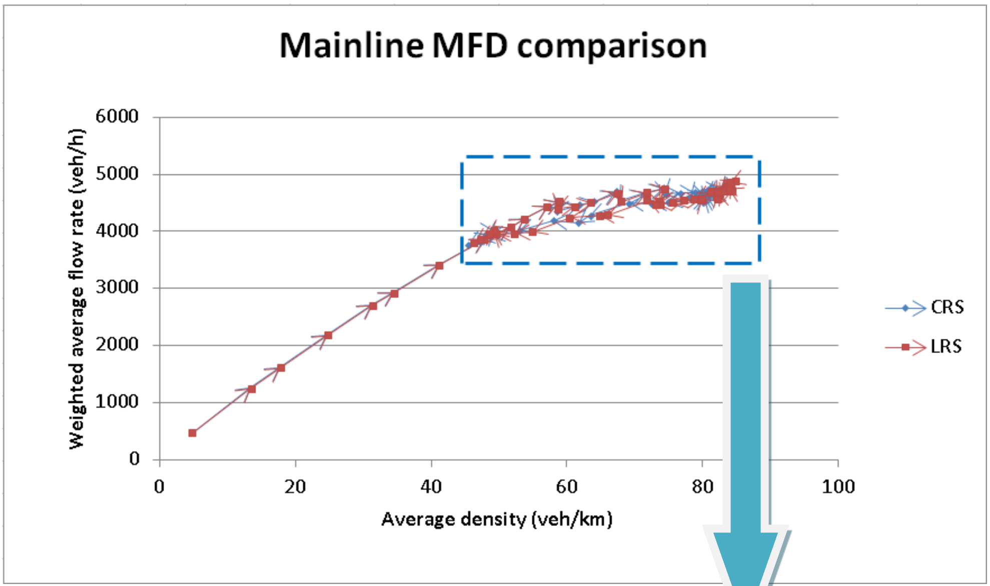
l is section length;

$\bar{k}$ is the average density of the network;

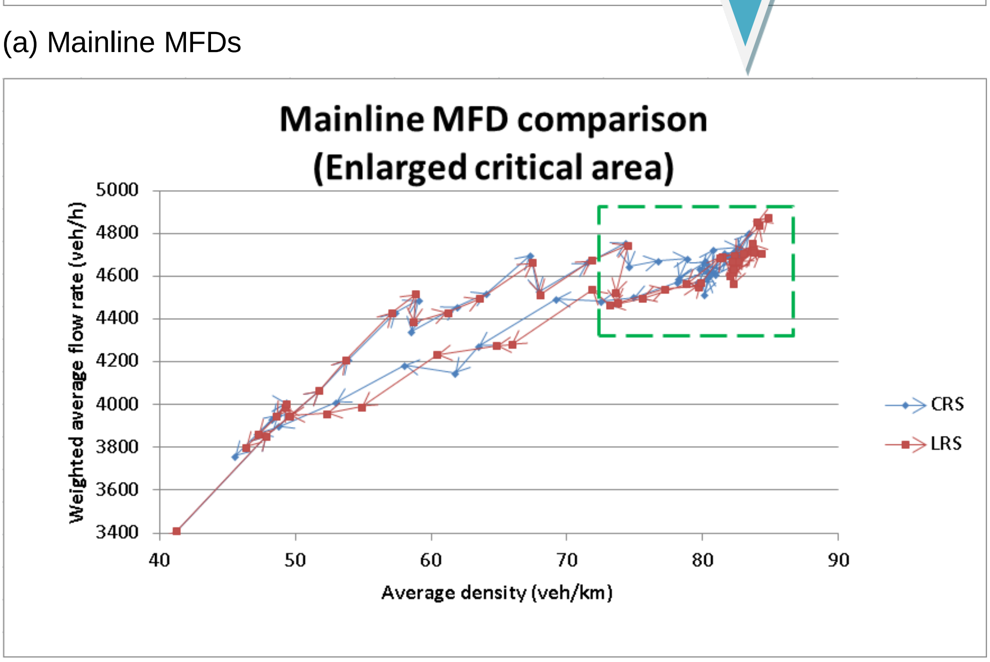
k is section density.

Figure 3 displays the MFDs for the LRS and the CRS scenario (The mainline MFDs are samples but all the replications produced similar patterns.). In the MFD, the arrows indicate the time sequences of the dots. Red dots are from the LRS scenario, and blue dots are from the CRS scenario. When looking at the whole MFD, the differences between the two scenarios are hard to see from Figure 3(a); the differences are supposed to happen when traffic flow are approaching critical area; therefore, the critical area (the blue dashed rectangle in Figure 3(a)) is enlarged and shown in Figure 3(b). It can be seen clearly from the enlarged figure that the CRS keeps higher network flow rate than from the LRS scenario (see the green broken rectangle) when the network is approaching congested. In addition, the standard deviation of the network flow rate during the congestion period (7:00 am to 8:30 am) are 74.2 veh/h in the CRS scenario and 93.1 veh/h in the LRS scenario, and this means the CRS stables the network flow rate after congestion. Besides, the mainline MFDs of the whole network show some fluctuations in network flow rate when the average density increasing. This is a result of two reasons. One is the way AIMSUN generating traffic demand. In the simulation network, the demand is given by traffic state with a 15-min interval (Chung, et al., 2011), so every time the change of traffic state causes fluctuation. The other one is the heterogeneity of the traffic conditions along the whole network. This is why no flow breakdown is observed from the MFDs.

Figure 3: Mainline MFD comparison – LRS and CRS



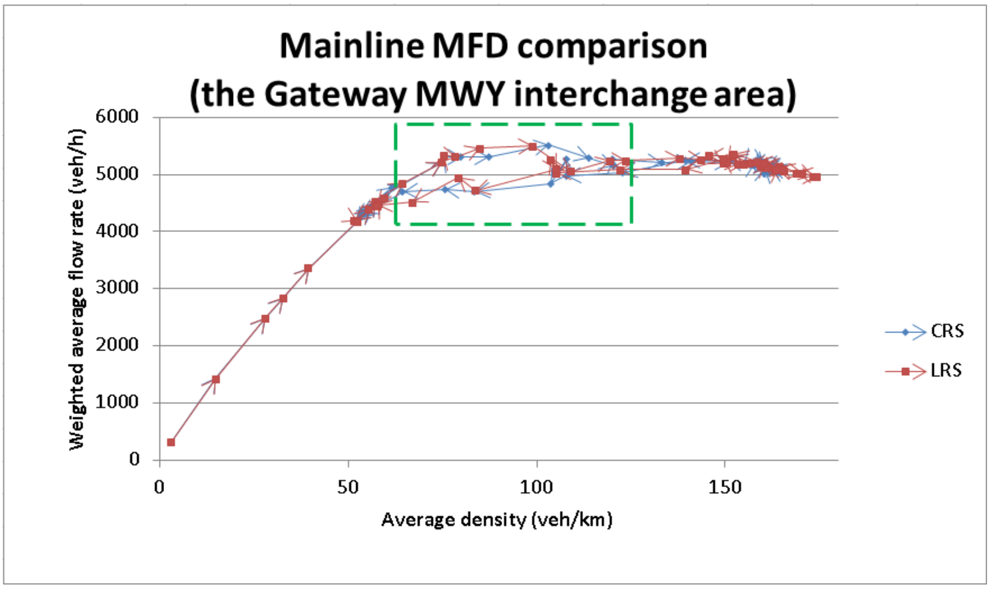
(a) Mainline MFDs



(b) Enlarged critical area

In order to investigate the impact of the CRS on the bottleneck area, Figure 4 illustrates the mainline MFDs of both scenarios for only the most significant bottleneck area: that is, the Gateway Motorway interchange (a weaving bottleneck) area from the upstream of the Loganlea Rd. on-ramp to the downstream of the Gateway Motorway off-ramp. The MFDs clear show the flow breakdown and capacity drop phenomenon in this area, because the traffic conditions are harmoniously governed by the Gateway Motorway interchange bottleneck. This implies that it is important to select participating sections for MFD to demonstrate the meaningful result. Additionally, the green dashed rectangle demonstrates the network flow transit to breakdown as average density increasing: the breakdown is delayed by the CRS.

Figure 4: Mainline MFDs of the Gateway Motorway interchange bottleneck area



6. Conclusion

This research presents a coordinated ramp signalling strategy. A special emphasis was placed on the practicality of algorithm to develop a field implementable strategy. Complex mathematical models and optimisation approaches were excluded because they require comprehensive and highly reliable traffic detector data, which is often implausible in the real traffic condition. The new strategy takes the rule-based heuristic framework with the feedback concept embedded in the control structure. The strategy is simple, transparent, and less data-dependent.

The performance of the proposed strategy was evaluated in simulation against the base case assuming no ramp signal and a local ramp signalling scenario employing the local ramp signalling algorithm (Jiang, et al., 2012). The simulation results revealed the followings:

- The mainstream traffic flow significantly improved with the coordinated strategy. The mainline traffic delay reduced by almost 55% over the base case scenario.
- The coordinated scenario was more effective in improving the mainline traffic flow. The mainline vehicle delay time decreased by 4.6% with the CRS scenario over the LRS scenario.
- The improved mainstream traffic flow was achieved by more balanced utilisation of ramp spaces to store traffic queues. Although the ramp delay time increased as a result of the coordination control, the total queue spillover time increased only slightly, 0.8% as compared with the LRS scenario; this also indicates that the strategy responses to traffic conditions quickly.

Acknowledgement

The authors would like to thank to Smart Transport Research Centre for funding this study.

References

Bogenberger, K., Vukanovic, S., & Keller, H. (2002). *ACCEZZ --- Adaptive Fuzzy Algorithms for Traffic Responsive and Coordinated Ramp Metering.* Paper presented at the Proceedings of the Seventh International Conference of ASCE.

Chung, E., Lee, B., & Jiang, R. (2012). STRC MM Coordinated Ramp Signalling Report. Brisbane: Smart Transport Research Centre, QUT.

Chung, E., Rahman, M., Bevrani, K., & Jiang, R. (2011). Evaluation of Queensland Department of Transport And Main Roads Managed Motorway. Brisbane: Smart Transport Research Centre, QUT.

Daganzo, C. F. (2005). *Improving City Mobility through Gridlock Control: an Approach and Some Ideas*. Paper presented at the U.C. Berkeley Centre for Future Urban Transport Working Paper UCB-ITS-VWP-2005-1.

Daganzo, C. F. (2007). Urban gridlock: Macroscopic modeling and mitigation approaches. *Transportation Research Part B: Methodological, 41*(1), 49-62.

Geroliminis, N., & Daganzo, C. F. (2008). Existence of urban-scale macroscopic fundamental diagrams: Some experimental findings. *Transportation Research Part B: Methodological, 42*(9), 759-770.

Geroliminis, N., & Sun, J. (2011). Hysteresis phenomena of a Macroscopic Fundamental Diagram in freeway networks. *Transportation Research Part A: Policy and Practice, 45*(9), 966-979.

Jacobson, L., Henry, K., & Mehyar, O. (1989). Real-time metering algorithm for centralized control. *Transportation Research Board*(1232), 17-26.

Jiang, R., Chung, E., & Lee, J. B. (2012). Local On-ramp Queue Management Strategy with Mainline Speed Recovery. *Procedia-Social and Behavioral Sciences, 43*, 201-209.

Kotsialos, A., Papageorgiou, M., Mangeas, M., & Haj-Salem, H. (2002). Coordinated and integrated control of motorway networks via non-linear optimal control. *Transportation Research-Part C Emerging Technologies, 10*(1), 65-84.

Lee, J. B., Jiang, R., & Chung, E. (2013). Traffic queue estimation for metered motorway on-ramps using loop detector time occupancies. *accepted by Transportation Research Record*.

Lipp, L., Corcoran, L., & Hickman, G. (1991). Benefits of central computer control for Denver ramp-metering system. *Transportation Research Record*(1320), 3-6.

Papageorgiou, M., & Kotsialos, A. (2002). Freeway ramp metering: an overview. *Intelligent Transportation Systems, IEEE Transactions on, 3*(4), 271-281.

Papamichail, I., Papageorgiou, M., Vong, V., & Gaffney, J. (2010). *HERO Coordinated Ramp Metering implemented at the Monash Freeway*. Paper presented at the Transportation Research Board Annual Meeting, 89th, 2010, Washington, DC, USA. http://80.33.141.76/origami/docs/vicroads.pdf

Virginia Department of Transportation. (1998). Ramp Metering Algorithm Description.

Yoshino, T., Sasaki, T., & Hasegawa, T. (1995). The Traffic-Control System on the Hanshin Expressway. *Computer, 25*(1), 94-108.