HERO Coordinated Ramp Metering Implemented at the Monash Freeway

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Abstract

A new heuristic traffic-responsive feedback control strategy HERO (HEuristic Ramp metering coOrdination) that coordinates local ramp metering actions at freeway networks is presented. The proposed coordination scheme is simple and utterly reactive, i.e., based on readily available real-time measurements without the need for real-time model calculations or external disturbance prediction. HERO employs an extended version of the feedback regulator ALINEA at a local level. The new strategy overcomes the problem of uncertain freeway capacity by targeting the critical occupancy for maximum throughput. HERO outperforms uncoordinated local ramp metering and approaches the efficiency of sophisticated optimal control schemes.

HERO has been implemented by VicRoads at 6 consecutive inbound on-ramps on the Monash Freeway in Melbourne, Australia. This pilot project was part of the Monash-CityLink-West Gate Upgrade (MCWU) Project. The obtained results show an increase of traffic throughput and a reduction of travel times. In order to maximize the performance across the entire 75 km route of the MCWU Project, HERO is currently under implementation at 58 more on-ramps.

Keywords: HERO; ALINEA; Coordinated ramp metering; Monash Freeway

1. Introduction

Ramp metering aims at improving the traffic conditions by appropriately regulating the inflow from the on-ramps to the freeway mainstream. Traffic-responsive ramp metering strategies, as opposed to fixed-time strategies, are based on real-time measurements from sensors installed in the freeway network and can be classified as local or coordinated.

Local ramp metering strategies make use of measurements from the vicinity of a single ramp. Most prominent examples of local ramp metering strategies are the demand-capacity (DC) and the occupancy (OCC) strategies (Masher et al., 1975), the ALINEA strategy (Papageorgiou et al., 1991, 1997) and its variations (Smaragdis and Papageorgiou, 2003; Smaragdis et al., 2004). DC and OCC are feed-forward disturbance-rejection schemes that target explicitly the flow capacity in the merge area and are based on mainstream measurements of flow or occupancy, respectively, upstream of the ramp. Recent works (Elefteriadou et al., 1995; Lorenz and Elefteriadou, 2001; Cassidy and Rudjanakanoknad, 2005) have demonstrated that the real flow capacity in a merge area may vary quite substantially from day to day even under similar environmental conditions. Naturally, highway capacity differences become even more pronounced in case of adverse environmental conditions (Keen et al., 1986; Papageorgiou et al., 2006a). Thus, any ramp metering strategy attempting to achieve a pre-specified capacity flow value will either lead to overload and congestion (on days where the real capacity happens to be lower than its pre-specified target value) or to underutilization of the infrastructure (on days where the real capacity happens to be higher than its pre-specified target value).

On the other hand, the critical occupancy, at which capacity flow occurs, seems to be more stable (Cassidy and Rudjanakanoknad, 2005), even under adverse weather conditions (Keen et al., 1986; Papageorgiou et al., 2006a). The ALINEA strategy and its variations are feedback control schemes targeting a set-point (typically the critical value) for the downstream occupancy. It is probably because of this critical-occupancy targeting feedback structure that ALINEA was found to lead to significantly better performance than DC and OCC strategies in several comparative field evaluations (Papageorgiou et al., 1997).

Coordinated ramp metering strategies make use of measurements from an entire region of the network to control all metered ramps included therein. Coordinated strategies may be more efficient than local ramp metering strategies when there are multiple bottlenecks on the freeway or restricted ramp storage spaces. Coordinated ramp metering approaches include multivariable control strategies (Papageorgiou et al., 1990; Diakaki and Papageorgiou, 1994) and optimal control strategies (Papageorgiou and Mayr, 1982; Chen et al., 1997; Zhang and Recker, 1999; Kotsialos et al., 2002; Kotsialos and Papageorgiou, 2001, 2004; Zhang and Levinson, 2004; Gomes and Horowitz, 2006; Papamichail et al., 2009). Multivariable regulators are derived from linearization of the strongly nonlinear traffic flow models, which limits their efficiency in case of heavy congestion. On the other hand, optimal control approaches employ relatively complex numerical solution algorithms that may be a burden for field application. This may be the main reason why field-implemented coordinated ramp metering strategies up to now have been based on heuristic rule-based approaches.

Bogenberger and May (1999) presented an extensive review of heuristic coordinated traffic-responsive ramp metering algorithms. A number of studies have compared the performances of these algorithms. Recently, Hadi (2005) summarized these comparisons for a number of heuristic coordinated strategies that have been implemented in USA, including the Zone and the Stratified Zone algorithms, the Bottleneck algorithm and the Helper algorithm. The main drawbacks of these approaches are:

- Most algorithms employ a feed-forward (rather than feedback) approach at either the local level or at the coordination level or both; this may lead to increased sensitivity with respect to various unexpected disturbances.
- All algorithms target pre-specified flow capacity values which, in view of the real capacity variations from day to day, may lead to either overload or underutilization of the freeway infrastructure.

In view of this situation, it would be desirable to have a coordinated ramp metering strategy that possesses the following features:

- It should coordinate local ramp metering actions in a suitable way so as to avoid the pitfalls of uncoordinated application.
- Involved algorithms should be feedback-based to reduce sensitivity to unexpected disturbances.
- It should be simple and transparent, e.g., rule-based.
- It should be reactive so that no real-time model involvement and no external disturbance prediction are needed.
- It should approach the efficiency of sophisticated optimal control schemes.
- It should be generic (i.e., directly applicable to any freeway network) without a need for cumbersome parameter calibration or fine-tuning.

A new heuristic traffic-responsive feedback control strategy that coordinates local ramp metering actions for freeway networks was indeed developed and was extensively tested via simulation (Papageorgiou et al. 2006b; Papamichail and Papageorgiou 2008) as well as in field implementations. This strategy was named HERO (HEuristic Ramp metering coOrdination) and possesses all features mentioned above. The proposed coordination scheme is simple and utterly reactive, i.e., based on readily available real-time measurements, without the need for real-time model calculations or external disturbance prediction. HERO employs an extended version of the feedback regulator ALINEA at a local level. The new strategy targets the critical occupancy for throughput maximization which is deemed more robust than targeting a pre-specified capacity value. HERO outperforms uncoordinated local ramp metering and approaches the efficiency of sophisticated optimal control schemes without the need for external disturbance prediction.

The rest of this paper is organized as follows. The modular structure of the generic HERO coordination software is presented in section 2. The field application of HERO at the Monash Freeway is discussed in section 3, while some field evaluation results are presented in section 4. Finally, section 5 concludes this paper.

2. HERO Coordination Software

A generic software has been developed that implements the HERO coordination scheme for any freeway network via suitable input configuration. The modular structure of this software is presented in Figure 1. The particular included modules are outlined in what follows.

Real-time data from the mainstream and the on-ramps are processed by the *Data Processing* module while the *Fail Safe* module decides on possible graceful-degradation actions in case of measurement failures. The *Activation/Deactivation* module switches the signal control on or off according to respective preset traffic conditions at the mainline.

The *ALINEA Core* module calculates the desired ramp exit flow at each ramp for local maximization of the mainstream throughput according to the ALINEA strategy. ALINEA is an I-type feedback control scheme targeting a set-point (typically the critical value) for the downstream occupancy. It should be noted that, since its development in the late 1980s, ALINEA has been successfully implemented at hundreds of ramps around the world. ALINEA has been extended recently and is now

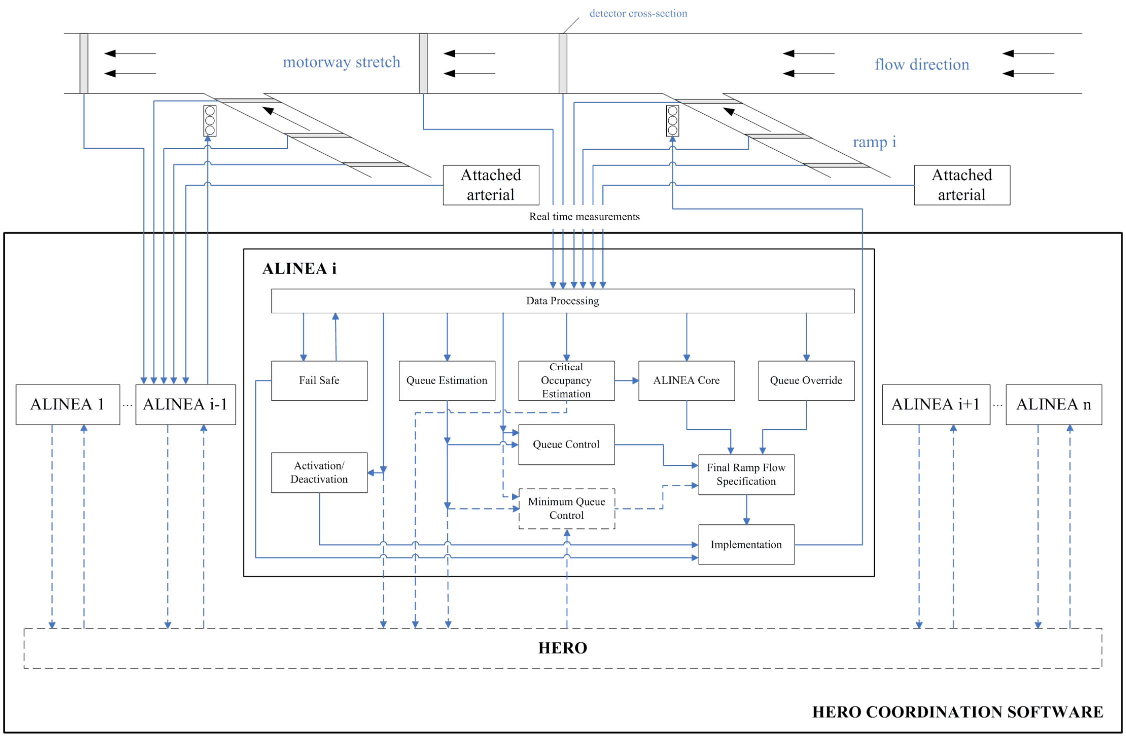

Figure 1: Modular structure of the HERO coordination software.

accompanied by a suite of algorithms (included in Figure 1) with some innovative features outlined in the corresponding module description below.

In case measurements from the merge area are not available, upstream measurements are used by a variation of ALINEA called UP-ALINEA (Smaragdis and Papageorgiou, 2003). In case of a bottleneck situated further downstream, the oscillations that may be observed using ALINEA are avoided by using its PI extension (Wang and Papageorgiou, 2006). This kind of bottlenecks may be due to a lane drop, a strong slope, a curvature or an uncontrolled downstream ramp. Finally, in case the targeted critical occupancy is not known, it can be automatically estimated (and updated) by activating the *Critical Occupancy Estimation* module which involves a Kalman filter based estimator (Smaragdis et al., 2004).

Creation of long ramp queues that would interfere with adjacent street traffic is avoided with the application of a queue control (Smaragdis and Papageorgiou, 2003) or an ordinary queue override policy in conjunction with ALINEA. These policies are realized by the *Queue Control* module and the *Queue Override* module, respectively. The ramp-queue length needed for queue control is calculated by the *Queue Estimation* module using ramp measurements and the Kalman filter estimator developed by Vigos et al. (2008). Remarkably, this method was taken over by other researchers who tested it in the field and compared it with two alternative estimation schemes (Wu et al., 2008); the reported results showed a clear superiority of the method versus both alternative schemes.

When ALINEA (or any other local ramp metering algorithm) is applied without coordination actions, it may be superseded by queue management actions, in which case a freeway congestion is created that travels upstream and activates local ramp metering at the next upstream on-ramp as well and so forth, leading to a spreading of ramp queues in reaction to the congestion that has formed. This phenomenon was observed in the field and was discussed in detail by Papamichail et al. (2009) based on reproducible simulation results with uncoordinated ALINEA application. It was concluded that independent (uncoordinated) application of ALINEA at each ramp (with limited storage space) may ameliorate the traffic conditions (compared to no control) but cannot always eliminate the congestion or minimize its detrimental effects on traffic flow efficiency. This discussion provided a sensible basis for developing a novel and efficient coordination scheme called HERO.

The *HERO* module in Figure 1 coordinates local ramp metering actions. Coordination is materialized via occasional appropriate setting of minimum ramp queue lengths that should be created and maintained at specific ramps, via superseding of ALINEA actions there, through the use of the *Minimum Queue Control* module. The basic philosophy of HERO may be summarized as follows:

(i) HERO identifies potentially active mainstream bottlenecks;

(ii) To retard or avoid ramp queue control of the concerned on-ramp (master) and the resulting mainstream congestion, HERO activates increasingly storage space via recruitment of upstream located slave-ramps.

(iii) The formed cluster of ramps is dissolved when the mainstream occupancy at the bottleneck or the master-ramp queue become sufficiently low.

Notice that, while HERO is recruiting increasingly slave ramps with corresponding minimum queues, the master-ramp's ALINEA continues to operate normally so as to continue to maximize the mainstream throughput at the potential bottleneck location.

The *Final Ramp Flow Specification* module is responsible for the choice of the ramp exit flow to be applied at the next control period while the *Implementation* module calculates the cycle time of the ramp metering traffic signals that corresponds to the final flow according to the ramp metering policy used (e.g. one car per green).

The HERO coordination software is currently being extended in order to handle multiple downstream bottlenecks, waiting-time constraints for vehicles queuing at an on-ramp and balancing of queues or waiting times on dual branch on-ramps by using separate signals for each branch.

3. Field Applications

Since the year 2000 Melbourne's freeways have become heavily congested with extended periods of flow breakdown. The Monash Freeway is a six-lane dual carriageway carrying in excess of 160,000 vehicles per day with up to 20% commercial vehicles and experiences long periods of congestion between 3 to 8 hours a day.

To address this congestion problem, the responsible road authority, VicRoads, undertook a technical overseas study tour to gain a detailed understanding of the physics of contemporary traffic flow theory, freeway flow management and freeway ramp metering. This study and subsequent analysis identified the need for:

- a system-wide approach to ramp metering that would provide the ability to coordinate on-ramps to balance flows across the network;
- a system-wide approach to resolving freeway bottlenecks by maximizing the available capacity of the freeway under all traffic loading and environmental conditions;

- a control logic that supported contemporary traffic flow theory.

VicRoads has undertaken detailed analysis of the various control logics used around the world which resulted in the recommendation to implement the HERO suite of algorithms which aligns with VicRoads freeway management objectives.

In early 2008, HERO was operational at 6 consecutive inbound on-ramps of the Monash Freeway extending from Jacksons RD to Warrigal RD. This $1M AUD pilot project is part of the Monash-CityLink-West Gate Upgrade (MCWU) Project. Significant benefits were demonstrated over the previous fixed-time ramp metering system which was replaced by HERO. The control logic has proven to be robust and transparent to traffic engineers. Transition to HERO has been seamless to motorists and provides significant flexibility and capability to operate the freeway close to optimal conditions. The economic payback period of the pilot project was just 11 days. The successful implementation and evaluation of HERO has lead to its rollout during 2009/10 at 64 sites across the entire 75 km route of the MCWU Project.

HERO field results are presented here below through its application during the PM peak of the 28th of March 2008. Figure 2 displays a graphical representation of the pilot project freeway stretch whereby the links of the graph represent freeway stretches with uniform characteristics, i.e. no on-/off-ramps and no major changes in geometry. The nodes of the graph are placed at locations where a major change in road geometry occurs, as well as at on-ramp and off-ramp junctions. Numbered bullets represent the available (but not necessarily HERO-utilized) detector stations.

During the PM peak a bottleneck is imminent downstream of the Forster RD on-ramp (ON_FORSTER in Figure 2). In order to address the problem, i.e. maintain the mainstream occupancy at the merge area of ON_FORSTER (the area of detector 7846) around its set-point (red dashed line in Figure 3(a)), ALINEA is acting locally and short queues are being formed as it can be observed in Figure 3(b). At 5:21 pm, the queue on ON_FORSTER exceeds a pre-specified threshold value and HERO is activated. ON_FORSTER becomes a master (M in Figure 3(b)) and recruits the first upstream on-ramp (i.e. ON_BLACKBURN) as its first slave-ramp (S1 in Figure 3(c)). Note that the queue that formed at ON_BLACKBURN just before 5:20 pm (and dissolved shortly after) was due to local control actions of ALINEA at that ramp. After the recruitment of the ramp as a slave, ALINEA is superseded and a queue is created and is maintained as a result of coordination. The maximum queue allowed on each on-ramp is represented by a red dashed line in the respective figure and is the set-point used by the queue controllers acting on the respective on-ramps.

The bottleneck at the merge area of ON_FORSTER persists and as a result more upstream on-ramps are gradually being recruited (S2, S3, S4 in Figure 3). It is noted that the small queue values estimated for ON_FERNTREE, ON_WELLINGHTON and ON_JACKSONS before their recruitment as slave-ramps are due to the number of moving vehicles on the respective on-ramps. The formed cluster of ramps (M,S1,S2,S3,S4) is dissolved at 5:27 pm as the queue on the master-ramp becomes sufficiently low. Thus, the imminent bottleneck activation downstream of the ON_FORSTER ramp could be avoided thanks to the coordinated HERO actions (and the local ALINEA actions).

It should be noted that HERO was also field-implemented in a 20-km stretch of the inbound A6 freeway in the south of Paris, France, in 2006, albeit in a simplified form due to lack of real-time on-ramp data in the control center; nevertheless, results indicated a clear improvement over the uncoordinated ALINEA case. Also, HERO has been adopted for field implementation at all urban on-ramps (some 40) of the ring-road freeway A10 around Amsterdam by the responsible road authority (Rijkswaterstaat) and the related implementation work is ongoing. Finally, a couple of further road authorities have expressed their interest for adopting HERO in their respective networks in the near future.

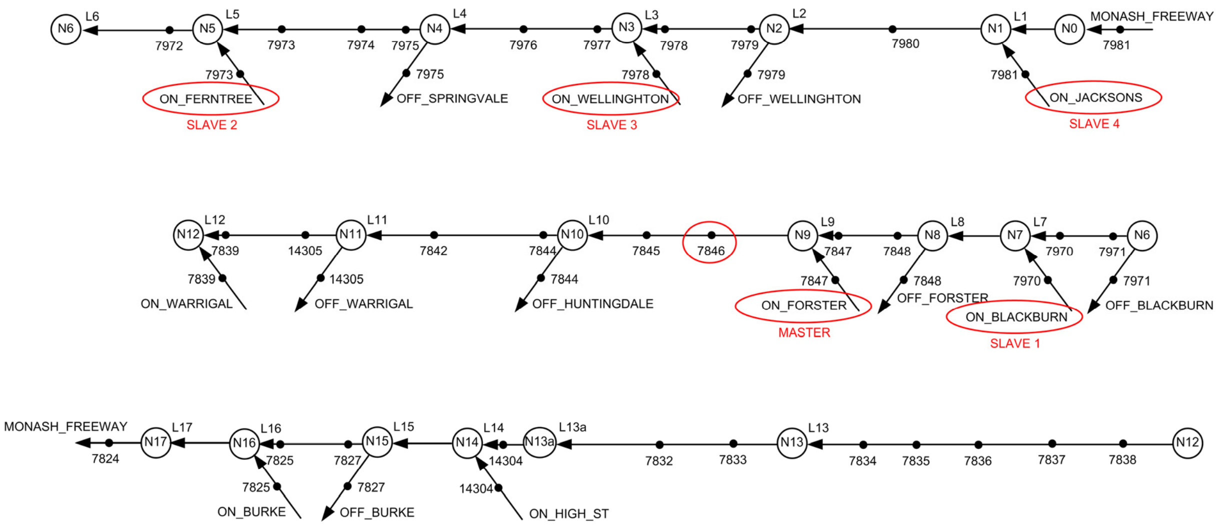

Figure 2: Representation of the pilot project freeway stretch.

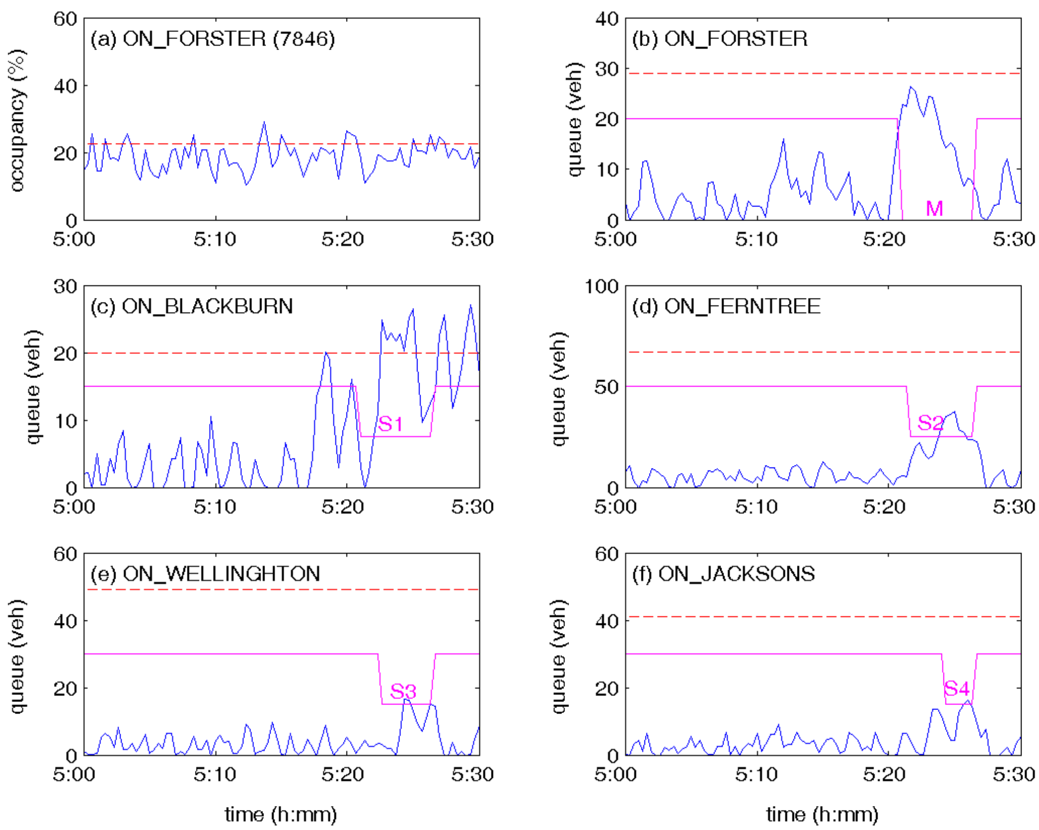

Figure 3: HERO coordination actions.

4. Evaluation Results

An evaluation of HERO's field performance was undertaken by VicRoads for the pilot project mentioned earlier. "Before and after" speed contour plots based on AM operation in 2007 and 2008 are shown in Figure 4 and Figure 5. HERO sensibly reduced the space-time extent of freeway traffic flow breakdown and provided significant improvements in throughput and travel speed. The AM peak evaluation revealed a 4.7% increase in average flow (on top of the previous system) and a 35% increase in average speed while the PM peak evaluation showed an 8.4% increase in average flow and a 58.6% increase in average speed. Comparisons involving the Austroads National Performance Indicators (ANPI) are displayed in Figure 6 for the AM peak. It is observed that there are very significant improvements in:

- productivity (a specific ANPI reflecting a combination of high speed and high volume on the freeway);

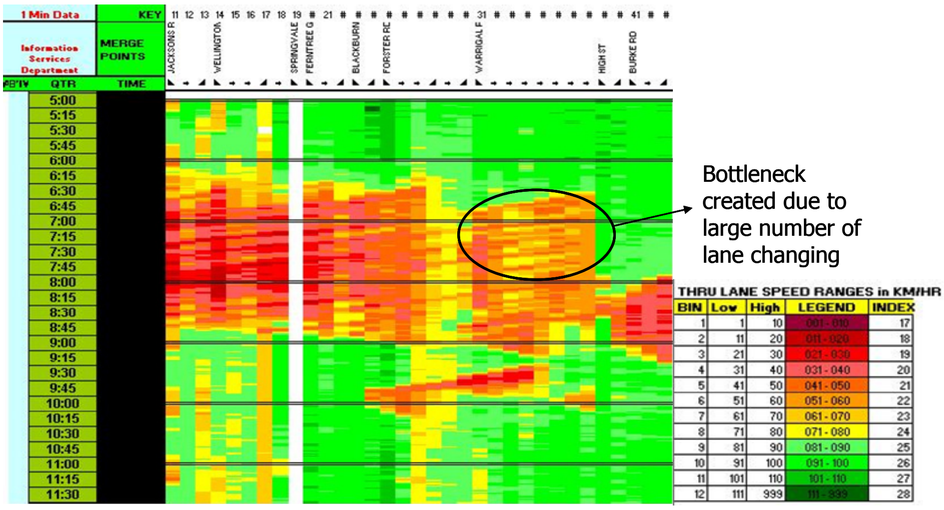

Figure 4: Fixed time metering – Typical day (AM) speed contour plot.

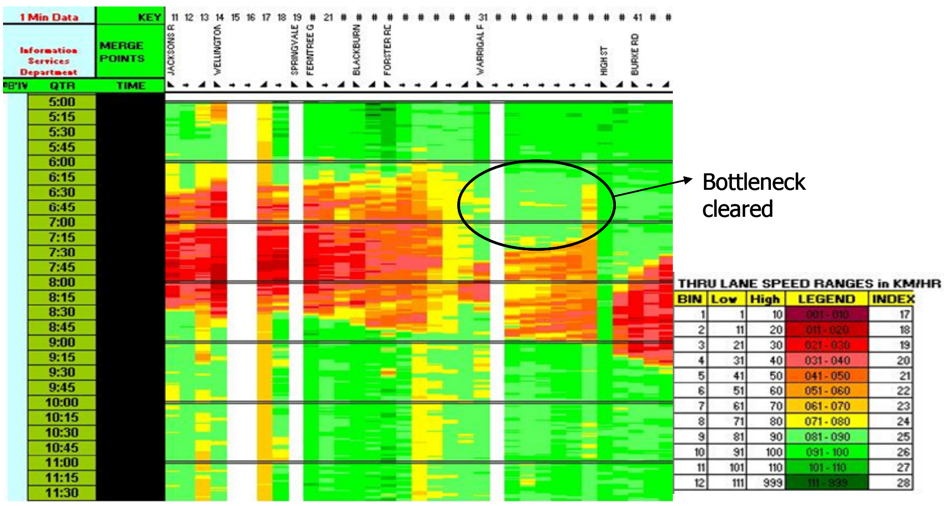

Figure 5: HERO – Typical day (AM) speed contour plot.

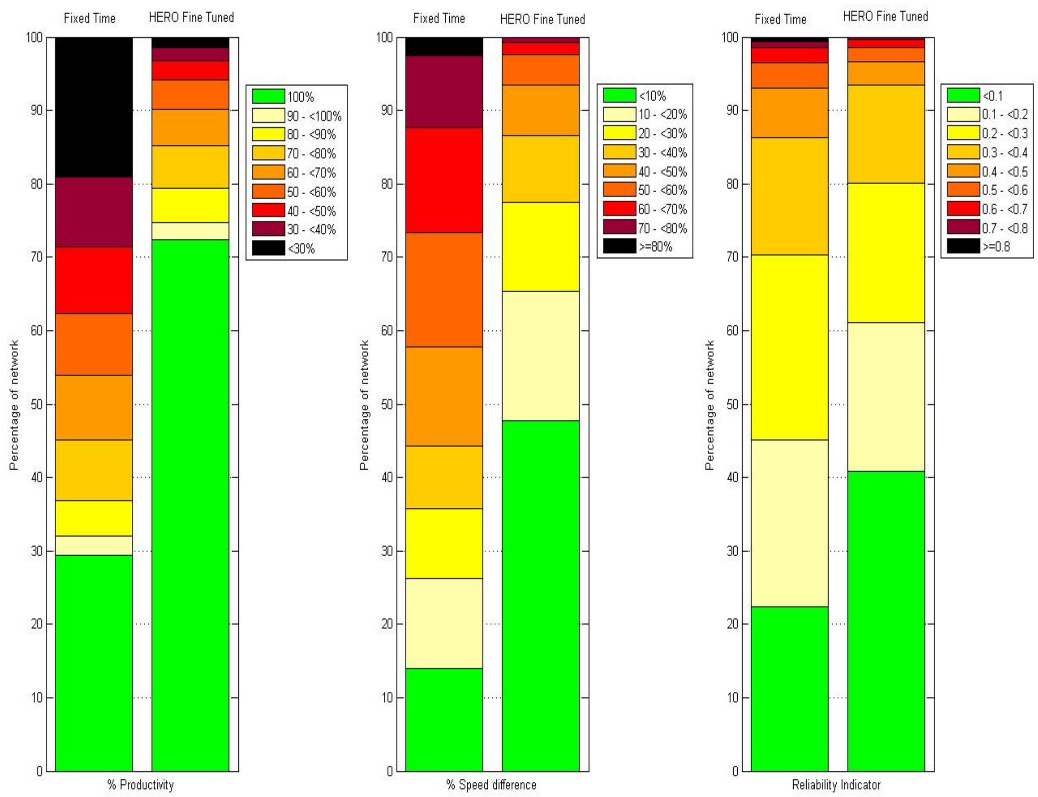

Figure 6: Austroroads national performance indicators.

- mean speed deviation (due to congestion) from the posted (maximum admissible) speed; and
- reliability (a specific ANPI reflecting travel time differences from day to day).

5. Conclusions

HERO, a new heuristic traffic-responsive feedback control strategy that coordinates local ramp metering actions for freeway networks, has been presented in this paper. The proposed coordination scheme is simple and utterly reactive, i.e., based on readily available real-time measurements without the need for real-time model calculations or external disturbance prediction. HERO employs an extended version of the feedback regulator ALINEA at a local level. The new strategy overcomes the problem of uncertain freeway capacity by targeting the critical occupancy for maximum throughput. HERO outperforms uncoordinated local ramp metering and approaches the efficiency of sophisticated optimal control schemes.

HERO has been implemented by VicRoads during a $1M pilot project at 6 consecutive inbound on-ramps on the Monash Freeway in Melbourne. The economic payback period of the pilot project was just 11 days. The obtained results show an increase of traffic throughput and a reduction of travel times. The successful implementation and evaluation of HERO has lead to its rollout during 2009/10 at 64 sites across the entire 75 km route of the MCWU Project.

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