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Systemic Evaluation of the HERO-Based Ramp Metering Algorithm Using Microsimulation

Demonstration Analysis Using a Sydney Motorway

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***Abstract*—Ramp meters impact not only the performance of the motorway, but also the performance of the arterial road network. The available literature on the HERO ramp metering system is used to implement it as closely as possible using AIMSUN Application Programming Interface (API). The implemented algorithm is evaluated using a network wide approach. In addition, a set of novel measures are introduced that facilitate the evaluation of the impacts of a ramp metering system on the entire network.**

***Keywords*—Ramp Metering; Evaluation; Coordinated Ramp Metering, HERO, Microsimulation.**

INTRODUCTION

Ramp metering (RM) employs traffic signals to control the traffic flow on ramps entering the motorway mainline. As a result, the mainline congestion and travel time are reduced, and the number of accidents in the merge areas also decline [1]. However, RM also impacts the performance of the arterial road network with the presence of queueing and the potential for a redistribution of traffic that creates congestion external to the mainline. Thus, it is important to evaluate the feasibility of the implementation of a RM solution in a systemic and rigorous manner. The current study aims to achieve this objective by providing an evaluation of a specific RM algorithm through the application of microsimulation modelling.

Since the early 1960s, a variety of RM algorithms have been implemented throughout the United States of America [2-4] and slowly expanded into Europe during the 1980s [5, 6]. In the last 20 to 25 years it has become prevalent within Australasia [7-9]; in particular within Auckland and Melbourne. In the current study an attempt was made to replicate a RM algorithm as closely as possible to the HERO based system implemented in Melbourne, Australia (STREAMS) [8].

The goal of the study is to evaluate the HERO RM algorithm using a large microsimulation network. The HERO algorithm has been evaluated typically in METANET (mesoscopic) [10, 11] or AIMSUN (microsimulation) [12, 13]. Each model has pros and cons in what it can be used to evaluate. For example, mesoscopic models are useful for assessing capacity drop on the mainline during congested environments. In this study a microsimulation model has been adopted for considering aspects of RM such as arterial diversions, on-ramp queueing and arterial integration.

The contribution of this paper are as follows, (1) implementation of a HERO-based algorithm (from here on referred to as $HERO_{Literature}$) using the AIMSUN *Application Programming Interface* (API) environment, (2) evaluation of the $HERO_{Literature}$ at a system level and (3) inclusion of additional criteria which should be considered during evaluation of RM systems. The presented analysis is relevant professionally since practical commercial solutions, such as STREAMS build on the HERO algorithm, as is examined in this paper.

MODEL DEVELOPMENT

The following section describes the methodology for the development of the Base scenario.

Network

The M2 motorway (situated in north-east of Sydney) and the adjacent arterial roads were used as the basis for the geometry of the network. The model includes 25km-long stretch of the motorway with 17 on-ramps and 15 off-ramps (Fig. 1).

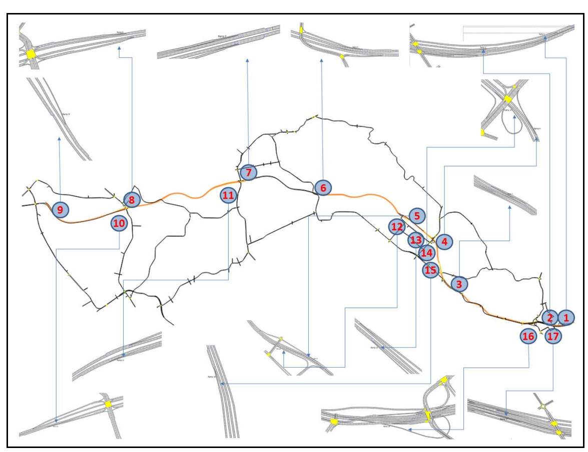

Fig. 1. Microsimulation Network Geometry and On-ramp Referencing

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Demand

The traffic demands were assigned to the network using *Origin-Destination* (OD) matrices for light and heavy vehicles. In order to evaluate the RM solution under different traffic conditions, six hypothetical demand conditions were developed (TABLE I.). A congested network was deemed necessary to effectively reveal the benefits of the implementation of a RM solution. The hypothetical demands were based on the theoretical capacities of the road infrastructure [14].

Arterial Signals

The arterial signals were coded for the intersections between the arterial network and a motorway ramp, intersections between two arterial roads or large intersections with slip lanes.

A total of 64 signalised intersections were coded using fixed time control plans. The phase sequence and timing were extracted from RMS SCATS database and manually fine-tuned to the "*1.5 Peaky*" demand condition. The remaining intersections were coded as priority controlled intersections.

Route Choice Model

The *Logit* stochastic route choice model was applied to evaluate the re-routing effect due to delays on the on-ramps. The route choice model was calibrated to a scale factor of 4.01, which was calculated using the average OD travel times obtained from the "*1.0 Flat*" demand condition [15]. This demand condition was considered to represent the moderate traffic condition.

IMPLEMENTATION OF HERO

The STREAMS RM system developed by TransMax, uses a HERO based algorithm. STREAMS RM system does not have a simulation plugin. The authors implemented the HERO-Based RM system within AIMSUN based on the available information (referred to as $HERO_{Literature}$) [7, 8, 16].

Aimsun Implementation

In order to better understand STREAMS an interview was conducted with VicRoads (the road authority in Melbourne where STREAMS RM system is currently operational). Previous implementation of HERO based algorithms in AIMSUN excluded some of the functionalities of STREAMS RM system such as queue management and ALINEA PI [12, 13]

The *Flow* function within AIMSUN was used to directly assign the RM rate to the controller, thus allowing for inclusion of the other modules of HERO as shown in TABLE II. provides a description of each module coded in the final API.

Calibration and Assumptions

The "*Peaky 1.5*" demand condition was used to fine tune the calibration of the $HERO_{Literature}$, as it is considered as 'the worst case'. The description of the main modifications and assumptions are provided below.

The API was coded to utilise the critical occupancy of the mainline to dynamically activate and deactivate the RM controllers. A threshold of O_{crit}-O_{meas}>0.25 was applied to turn the metering ON, and a threshold of O_{crit}-O_{meas}<0.20 was applied to turn a meter OFF. Notwithstanding, in order to turn a meter ON or OFF the previously mentioned condition must have been met over three consecutive cycles.

TABLE I. DEMAND CONDITIONS

Demand Profile	Demand Multiplier		
	Low (25k PCU)	**Typical (50k PCU)**	**Extreme (75K PCU)**
Uniform Profile	0.5 Flat	1.0 Flat	1.5 Flat
Concentrated Profile	0.5 Peaky	1.0 Peaky	1.5 Peaky

TABLE II. LITERATURE USED TO DEVELOP $HERO_{LITERATURE}$

Module	Description	Main References
ALINEA Core	Includes ALINEA I-type and PI depending on the distance between the on-ramp and the detector station	[11, 17]
Minimum Queue Control	Coordination of on-ramps by forming a minimum queue on the (upstream) on-ramp/s	[8, 11]
Queue Estimation	Estimates the on-ramp queue length (in vehicles) using a *Kalman Filter* technique	[18]
Queue Override	If the occupancy measurements from the detector at the entrance to the on-ramp is above a threshold, the metering rate is relaxed to avoid arterial spill-back	[19]
Critical Occupancy Estimation	Continuously updates the critical occupancy at each station using a *Kalman Filter* technique	[20]
Final Ramp Flow Specification	Selects the appropriate flow rate from each module to apply to the on-ramp	[11]

Red time limits of minimum (2 sec) and maximum (16 sec) were set as per the *VicRoads RM Handbook* [16].

To calibrate the queue length estimation module, the Kalman gain factor values were fine-tuned for the on-ramps with large storage capacity [18, 21]. The gain factor K was tested within the range of 0.05 to 0.3, starting with the recommended 0.1 value. For longer on-ramps the smaller K values were primarily tested. A second occupancy detector was coded for on-ramp 9.

The ALINEA I-type algorithm can be used under the assumption that the majority of vehicles leaving the metered ramp will reach the relevant mainline detector within one time step (i.e., 16 Seconds) [17]. The mainline detector stations that were within 356 m to the RM stop line were assigned the I-type algorithm, and the PI-ALINEA algorithm was assigned to the stations further downstream. The stations at distance of 3 km or more were excluded from the algorithm.

The queue override module was activated by a detector placed at the entrance of the on-ramp. A threshold occupancy of 80% was applied [8]. Some detectors were made longer to reduce the possibility of *Zero Speed Zero Occupancy* issues.

The critical occupancy module was used to obtain the initial critical occupancies values for the 89 stations along the mainline. The final critical occupancies were obtained by the flow vs occupancy charts and manual fine-tuning.

The linkage between metered on-ramps determines for each on-ramp, the list of upstream on-ramps it can request assistance when needed. The linkage between metered on-ramps was selected based on the proportion of traffic from an up-stream on-ramps reaching the mainline bottleneck/s associated with each on-ramp, i.e.: two on-ramps were linked, if the amount of traffic leaving an upstream on-ramp had a significant influence on the operations of a downstream on-ramp. Fig. 2. shows the final linkage settings for $HERO_{Literature}$.

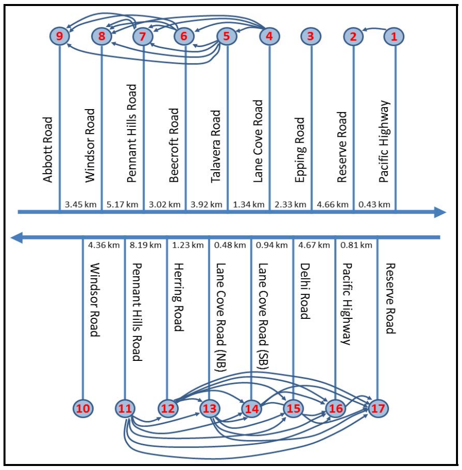


Fig. 2. Linkage Between Metered On-ramps in $HERO_{Literature}$

Evaluation Measures

Overall Network Performance Criteria

The performance metrics reported for the entire network include: *Total System Travel Time* (TSTT), *Vehicle Kilometres Travelled* (VKT), speed, and exit flow. The network wide performance criteria are arguably the most important metrics to consider as the road network is assessed holistically. The metrics reported directly from AIMSUN should be interpreted with caution when comparing scenarios, as these measures typically exclude the vehicles that did not exit the network by the end of the simulation period. The methodology for calculating the default AIMSUN outputs is described in [15]. We use a modified metric for *TSTT* so that all the vehicles are considered regardless of their exit time:

$$TSTT_{Calc}=TTT_{AIMSUN}+TT_{last2:30}\times Veh_{in}+T_{Sim}\times Veh_{AvgVirtualQ} \quad (2)$$

TTT_{AIMSUN} is the travel time of all vehicles that exited the network by the end of the simulation period. $TT_{last2:30}$ is the average travel time of the vehicles existing the network in the last 2.5 minutes of the simulation period. $Veh_{avgVirtualQ}$ is the average number of vehicles unable to enter the network (i.e., in a virtual queue) during the simulation period, and T_{Sim} is the length of the simulation period (i.e., 2 hours). The term ($T_{Sim}\times Veh_{avgVirtualQ}$) assumes that vehicles which are in the virtual queue are stationary. This measure considers all vehicles in the demand matrix and is comparable across scenarios.

On-ramp Performance Criteria

RMs cause additional delays at the on-ramps which may lead to spill-backs onto the arterial. Accordingly, the following metrics were used to evaluate the on-ramps performance:

- **Percentage of Time at Maximum Queue (%).** The proportion of time that the occupancy of the detector at the entrance of the on-ramp was greater than 80%.
- **Maximum Observed Queue (vehicles).** The queues on the on-ramps were manually observed throughout the simulation.
- **Maximum number of Affected Intersections (number of intersections).** The number of intersections affected by the "*Maximum Observed Queue*".

Obtaining a measure of queuing is not an easy task, particularly when the queues spill-back in multiple directions in the upstream arterial roads. By considering the above measures concurrently, it is possible to obtain an indication of the queueing condition at the on-ramps. The length of time the on-ramp queue reaches the entrance to the on-ramp provides an indication of the frequency of the queue spill-back. While the maximum observed queue (and the maximum number of affected intersection) provides an indication of the extent of the issues caused by the queue. A limitation of this methodology is that in some scenarios the maximum queue observed is primarily caused by the arterial network, in which case the on-ramp queue is a minor contributor to the maximum queue.

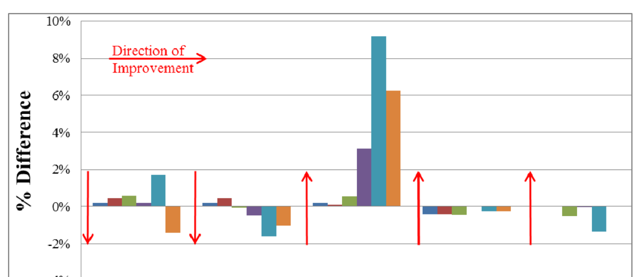
Results And Discussion

Overall Network Performance

The differences between the network-wide metrics for the Base and $HERO_{Literature}$ scenarios is shown in Fig. 3. The results indicate that the $TSTT_{Calc}$ has improved by 1.4% for the "*1.5 Peaky*" demand condition (a dis-benefit was seen the other five demand condition). The 'fine-tuning' of both the arterial signals and the RM was conducted for the "*1.5 Peaky*" demand condition. The result indicates the importance of calibration particularly for RM.

The default $TSTT_{AIMSUN}$ statistics produced by AIMSUN is provided as a point of reference and highlights the need for $TSTT_{Calc}$. The values of the *Exit Flow* show that the total number of vehicles that exit the network by the end of the simulation period fluctuates between each scenario. Resulting in a different number of vehicles included in the $TSTT_{AIMSUN}$ statistics. For example, in the "*1.5 Flat*" demand condition more vehicles are included in the $TSTT_{AIMSUN}$ for the Base scenario compared to the $HERO_{Literature}$ scenario.

The mainline speeds have increased due to RM for all six demand conditions. The arterial speeds have reduced slightly because of the diversion of traffic from the mainline to the arterials.



	TSTT (Calculated)	TSTT (AIMSUN)	Mainline speed	Arterial speed	Exit Flow
0.5 Flat	0.2%	0.2%	0.2%	-0.4%	0.0%
0.5 Peaky	0.4%	0.5%	0.1%	-0.4%	0.0%
1.0 Flat	0.6%	-0.1%	0.6%	-0.5%	-0.5%
1.0 Peaky	0.2%	-0.5%	3.1%	0.0%	0.0%
1.5 Flat	1.7%	-1.6%	9.2%	-0.3%	-1.4%
1.5 Peaky	-1.4%	-1.0%	6.3%	-0.3%	0.0%

Fig. 3. Difference in Network Wide Statistics ($HERO_{Literature}$ - Base)

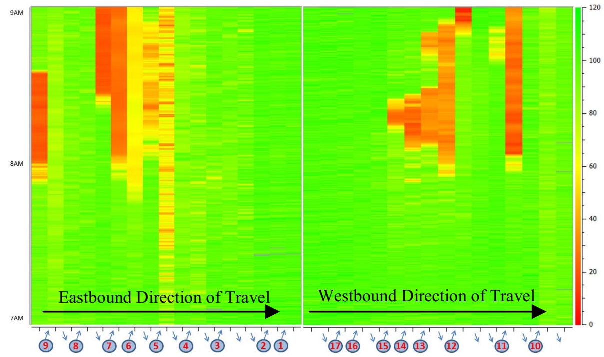


Fig. 4. Speed Contour Plots in KM/h (Base, "*1.5 Flat*")

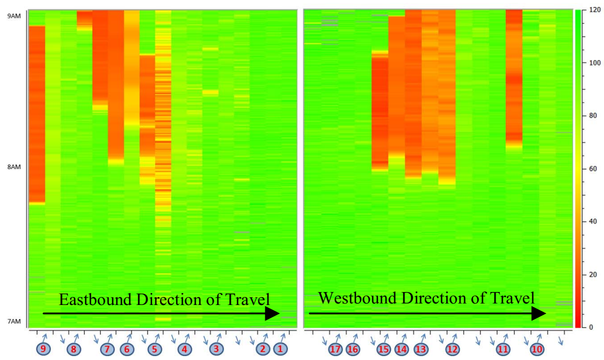


Fig. 5. Speed Contour Plots in KM/h (Base, "*1.5 Peaky*")

Mainline Performance

Fig. 8 shows the *AustRoads Productivity Graph* which considers both speed and flow, indicating the performance of the mainline under different scenarios. The methodology used in production of this graph is presented in [22]. The productivity graph show that the productivity of the mainline improves for the $\text{HERO}_{\text{Literature}}$ scenario across the six demand conditions.

Fig. 4 to Fig. 7 show the change in *Speed Contour Plots* for the two higher demand conditions. The speed measurements are obtained from mainline detector stations placed between each ramp. The figures indicate that the $\text{HERO}_{\text{Literature}}$ scenario has significantly higher speeds for a longer period of time. The figures show the effect of a number of bottlenecks along the network and how the impact of the shockwaves has reduced significantly in the $\text{HERO}_{\text{Literature}}$ scenario. The other four demand conditions all follow a similar pattern but have not been presented to save on space. It is noted that in some sections of the mainline speed improvements of up to 34% was observed for the "*1.5 Peaky*" demand condition.

Fig. 9 shows that the mainline flow follows the demand profile. As the demand multiplier is increased the capacity of the mainline is reached and the mainline flow plateaus. Unlike the field observations, the capacity drop during congested conditions is not present in the microsimulation results [23, 24]. In the microsimulation results, large flow rates are achieved even at significantly lower speeds. This is currently one of the limitations of the state-of-the-art microsimulation models.

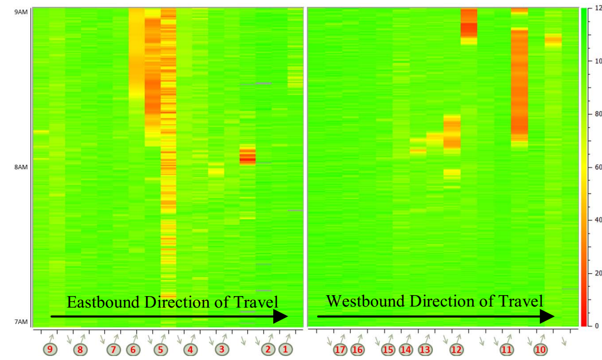


Fig. 6. Speed Contour Plots in KM/h ($\text{HERO}_{\text{Literature}}$, "*1.5 Flat*")

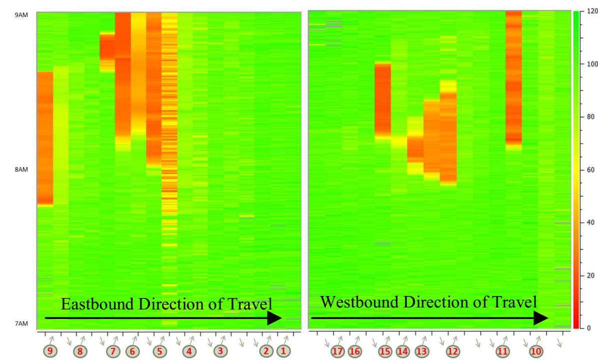
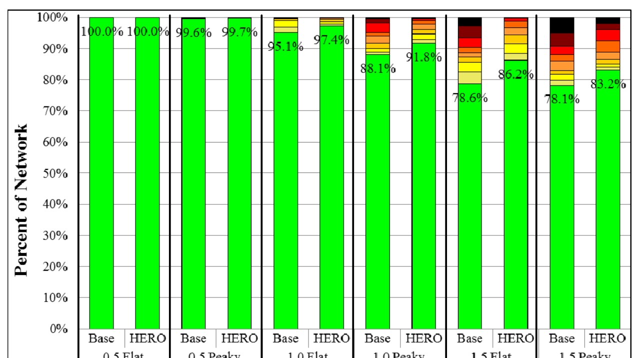


Fig. 7. Speed Contour Plots in KM/h ($\text{HERO}_{\text{Literature}}$, "*1.5 Peaky*")



	Base	HERO	Base	HERO	Base	HERO	Base	HERO	Base	HERO	Base	HERO
	0.5 Flat		0.5 Peaky		1.0 Flat		1.0 Peaky		1.5 Flat		1.5 Peaky	
30	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.4%	0.1%	2.7%	0.1%	5.2%	2.3%
30-40	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	1.5%	0.2%	3.9%	0.2%	4.2%	1.7%
40-50	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	3.1%	0.6%	3.2%	0.9%	2.6%	3.8%
50-60	0.0%	0.0%	0.0%	0.0%	0.1%	0.1%	1.0%	1.2%	1.5%	2.0%	2.0%	3.4%
60-70	0.0%	0.0%	0.1%	0.0%	0.3%	0.5%	2.3%	1.7%	1.6%	2.4%	3.1%	2.5%
70-80	0.0%	0.0%	0.1%	0.1%	0.6%	0.7%	1.8%	1.5%	1.6%	2.9%	1.2%	1.5%
80-90	0.0%	0.0%	0.1%	0.1%	2.0%	0.8%	1.0%	1.7%	3.0%	3.0%	2.0%	1.0%
90-100	0.0%	0.0%	0.1%	0.1%	1.9%	0.4%	0.8%	1.1%	4.0%	2.3%	1.7%	0.8%
100	100.0%	100.0%	99.6%	99.7%	95.1%	97.4%	88.1%	91.8%	78.6%	86.2%	78.1%	83.2%

Fig. 8. Comparison of the Mainline Productivity

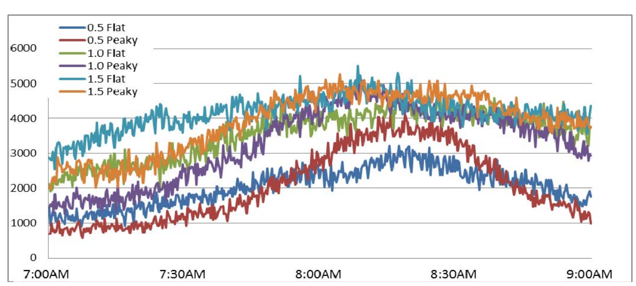


Fig. 9. Average Flow in veh/h (Eastbound, $\text{HERO}_{\text{Literature}}$ Scenario)

On-ramp Performance

Ramp meters cause an increase of queue length at the on-ramps that may spill-back onto the adjacent arterial network. Queue spill-backs can have significant negative effects on the network performance. This section focuses on the queue spill-back. Due to space restrictions the two most representative traffic conditions have been presented.

TABLE III. shows the two on-ramps that were observed to spill-back onto the arterial network for the "*1.0 Flat*" demand condition. The queue spill-back from the on-ramps may join other queues created by the arterial network. The *maximum queue* and *number of intersections affected* is a combined effect of the on-ramp queue and the queues within the arterial network. For example, the comparison of the Base and $\text{HERO}_{\text{Literature}}$ scenarios for on-ramp 8 shows a relatively small increase in the percentage of time at maximum queue (i.e., 12.6%), while a large increase in the length of the *Maximum Observed Queue* (i.e., 268 veh). On-ramp 9 shows an opposite result (i.e., 35.6% and 162 veh respectively), indicating that the reported queue is primarily due to on-ramp 8 and less so from the arterial network.

TABLE III. ON-RAMP PERFORMANCE ("*1.0 FLAT*")

On-ramp ID*	Queue Capacity (vehicles)		Queue Performance Measures					
			Percentage of time at Max Queue		Maximum Observed Queue (vehs)		Maximum Affected Intersections	
	BN[a]	SL[a]	Base	HERO	Base	HERO	Base	HERO
8	128	118	8.7%	21.3%	408	676	3	4
9	186	258	9.1%	44.7%	190	352	0	2

[a] Capacity of the on-ramp is measured from: BL = Bottleneck on the on-ramp, SL = Stop Line.

The queue performance measures for the "*1.5 Peaky*" demand condition is presented in TABLE II. . Eight on-ramps were observed to exceed the available queue storage capacity. On-ramps 8, 13 and 14 have significant queues due to ramp meters, increasing the percentage of time at maximum queue by more than 25%, and affecting an additional four arterial intersections. This is an indication that the design of the ramps does not adequately meet the requirements of RM for the "*1.5 Peaky*" demand condition.

TABLE IV. ON-RAMP PERFORMANCE ("*1.5 PEAKY*")

On-ramp ID*	Queue Capacity (vehicles)		Queue Capacity (vehicles)					
			Percentage of time at Max Queue		Maximum Observed Queue (vehs)		Maximum Affected Intersections	
	BN[b]	SL[b]	Base	HERO	Base	HERO	Base	HERO
6	69	79	9.8%	27.6%	132	436	0	3
8	128	118	11.1%	38.0%	2624	3431	6	10
9	186	258	54.2%	59.3%	1740	2308	3	5
11	359	369	7.3%	15.6%	790	930	1	2
12	117	127	7.3%	19.6%	194	300	1	1
13	100	64	0.0%	29.3%	62	520	0	4
14	-	52	13.6%	41.6%	50	570	0	4
15	105	115	14.0%	28.2%	184	334	1	2

[b] on-ramp capacity is measured from: BL = Bottleneck on the on-ramp, SL = Stop Line

The proposed on-ramp performance metrics can be used to highlight the on-ramps that may require queue mitigation measures. On-ramps with relatively large proportion of time at the maximum queue and long maximum queues should be considered when implementing the RM system. For example, the design of the eight on-ramp in TABLE IV. should be considered for the "*1.5 Peaky*" demand condition.

Arterial Diversion (re-routing)

The additional delays experienced by road users when on-ramps are metered, can result in a diversion (re-routing) of the traffic from the motorway to the arterial network.

The redistribution of traffic throughout the network due to the implementation of the $\text{HERO}_{\text{Literature}}$ was assessed by comparing the VKT along the arterial sections of the hypothetical network. The network flows are different in each model and as a result the absolute VKT cannot be directly compared, because each model has a different total number of vehicles included within the VKT statistics. The proportion of VKT traveling on the arterial roads as compared to the mainline is less sensitive to the total throughput and is used to compare the traffic diversion between scenarios.

The proportion of the total network VKT that was on the arterial roads is shown in Fig. 10. Approximately 40% of the total VKT is on the arterial networks with a demand of 0.5. As the demand increases and the on-ramp delays increase due to ramp metering, the proportion of VKT on the arterial network increases. The proportion of VKT on arterials increases by 5% in the "*1.5 Peaky*" demand condition. The change in proportion of arterial VKT due to $\text{HERO}_{\text{Literature}}$ is 0.5% or less depending on the demand condition. This is equivalent to more than 3,900 VKT for the "*1.5 Flat*" demand condition. This is significant when considered over the life of the project, and should be minimised as much as possible.

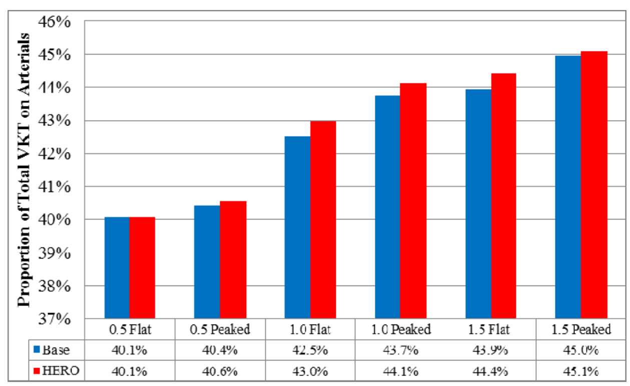


Fig. 10. Proportion of Total VKT on the Arterial Network

CONCLUSIONS

A network wide evaluation of $\text{HERO}_{\text{Literature}}$ RM system was conducted using the microsimulation platform (AIMSUN). The $\text{HERO}_{\text{Literature}}$ API is based on the STREAMS System which has been implemented in Melbourne. The evaluation is conducted on a road network based on 25 km stretch of the M2 motorway and its parallel arterials (situated at north-east of Sydney). Six hypothetical demand scenarios were tested to check the performance of the RM system under varying traffic conditions.

The authors implemented the HERO algorithm using the AIMSUN API. The implemented API considers majority of the modules included in the available peer reviewed literature. The specific commercial products (e.g., STREAMS) are continually evolving which without a simulation plugin, makes any evaluation temporary. The authors, to the maximum extent possible, calibrated the $HERO_{Literature}$ to the "*1.5 Peaky*" demand condition. Nonetheless, the commercial teams would likely have more deployment experience for the calibration task.

The $HERO_{Literature}$ was found to provide a maximum mainline speed benefit over various motorway sections of approximately 34% (for the specific network and demand profiles examined), however the arterial speeds were found to be affected negatively in certain cases (thereby establishing the need to examine broader metrics than the mainline motorway). For instance, the network-wide impact (considering both mainline and arterials) on total system travel time was found to range from -1.4% to 1.7%, further highlighting that the implementation of RM could result in network improvements or deterioration depending on the specific case being examined, calibration 'fine-tuning' and the coordination with the arterial street network. In other words, even in some cases where the mainline improved, the overall system could suffer (e.g., if RM was not optimally deployed with a consideration of the network impact). This highlights the need to consider metrics beyond only mainline conditions and stresses overall deployment, planning and configuration.

Though motorway data is available in some cases, the lack of arterial network data and, more critically, the simultaneous infrastructure improvements during the implementation of RM limits the opportunity to conduct network level analysis or conduct a controlled before and after analysis based on available data sets. This highlights the need for simulation tools that can be used to evaluate such scenarios.

The capabilities of microsimulation models remains an active field of research and development. For instance, even state-of-the-art simulation approaches may not fully account for the full benefits of RM. However, such models are the only tool capable of conducting controlled experiments over numerous hypothetical cases with clearly calculable metrics at both the mainline and network level. Thus current limitations of microsimulation models such as the mainline capacity drop in congested environment remains an open research question and should be considered in future research.

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