Assessing Ramp Metering and Variable Speed Limits Strategies for Auckland Motorway

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Abstract: Ramp metering (RM) and variable speed limits (VSL) are two important Intelligent Transportation Systems (ITS) tools aimed at improving the performance of motorway systems. The former is widely used all around the world to regulate on-ramp traffic while the latter is still an emerging technology that can be deployed in the mainline immediately upstream side of on-ramps to create some merging space for entering traffic. This paper assesses the performances of two ramp metering algorithms namely ALINEA and HERO individually and in combination with VSL strategies for a critical bottleneck section of Auckland Motorway using AIMSUN micro-simulation. ALINEA is the most prominent local RM algorithm while HERO is a rule-based coordinated RM algorithm. Total travel time and Gini coefficient were the two important performance indicators used to measure the efficiency and equity of the motorway system respectively. Results showed strengths and weaknesses of these tools for the motorway system.

Keywords: Ramp metering, variable speed limits, efficiency, equity, AIMSUN

1. INTRODUCTION

With the emphasis of governments on wealth creation, demand for travel is increasing all over the world. The growth rate is particularly higher in and around metropolitan areas where most of the economic activities are concentrated. Motorways that are usually expected to provide a level of service higher than that of other urban streets; are experiencing extensive daily traffic congestion and often reaches stop-and-go state during peak periods. Adding capacity of road infrastructure is not always a viable option due to various social, spatial, financial and environmental constraints. Intelligent transportation systems (ITS) based countermeasures aim for optimal utilization of available infrastructure incorporating distributed control and coordination system to ensure a safer, efficient and reliable transportation system. Ramp metering (RM) and variable speed limits (VSL) are two important Intelligent Transportation System tools aimed at improving performance of motorway systems. RM is widely used all around the world to regulate on-ramp traffic and is commonly regarded as one of the most direct and efficient countermeasures to mitigate traffic congestion on motorways (Papageorgiou, 2003). RM improves performance of motorways by regulating on-ramp flow to keep mainline flow under its capacity. VSL is an emerging technology that can be deployed in mainline immediately upstream side of on-ramps to create some merging space for the traffic entering mainline.

Traffic responsive RM strategies, as opposed to fixed-time strategies are based on real-time measurements from sensors installed in motorway network. Over the years, a number of traffic responsive RM strategies have been developed, which can be classified into two group namely local ramp metering (LRM) and coordinated ramp metering (CRM). In LRM, the metering rate is determined based on local traffic conditions whereas CRM utilizes system-wide traffic measurements from an entire region of the network to control all on-ramps with in that region. ALINEA is the most prominent example of the LRM, which targets to a set point for the downstream occupancy or density (Papageorgiou et al., 1991). A review of other LRM strategies is presented in Papageorgiou and Kotsialos (2002). CRM have advantage over LRM when dealing with multiple bottlenecks, limited on-ramp storage spaces and inequity to travellers. A great deal of research works conducted in the past to come up with a number of CRM strategies, which can be broadly classified into three categories namely optimal control strategies (Papageorgiou and Mayr 1982; Zhang and Recker 1999; Kotsialos et al., 2001, Kotsialos, 2004; Gomes and Horowitz, 2006),hierarchical control strategies (Papageorgiou 1983;May 1976;Geroliminis et al., 2012), and heuristic rule-based strategies (MnDOT 2003; Jacobson et al. 1989; Paesani et al. 1997; Papamichail et al. 2010).

Optimal control strategies employ relatively complex numerical solution algorithms, making it quite challenging to implement in the field. This might be the reason that most of CRM strategies implemented in the field are heuristic rule-based strategies. An extensive review of heuristic CRM strategies can be found in Bogenberger and May (1999). Hadi (2005) compared the performance of a number of CRM strategies implemented in United States including Zone, Stratified Zone, Bottleneck and Helper. More recently, Papamichail and Papageorgiou (2008) proposed a HEuristic Ramp metering coOrdination (HERO) strategy to overcome some of the drawbacks witnessed in the previously discussed strategies. It claims to have achieved efficiency close to that of some sophisticated optimal control strategies discussed earlier. Besides, it is a simple and transparent strategy that employs an extended version of ALINEA at the local level and more importantly it does not require any model to predict external disturbances. HERO strategy is in operation in Motorway A6 in Paris, France and Monash Freeway in Melbourne, Australia. Papamichail et al. (2010) conducted a before and after study of Monash Freeway and reported that HERO strategy has improved efficiency of the freeway system. The study did not touch on equity aspect of the system.

VSL can be an effective traffic control measure to improve both safety and efficiency of motorway systems (Hegyi et al., 2005, Abdel-Aty et al., 2006). Mandatory VSL are generally preferred; which is legally equivalent to fixed speed limits and may even be automatically enforced to increase driver compliance. In recent years, the use of VSL in motorways is rapidly increasing worldwide while the first use of VSL record back to more than three decades ago in Germany. Several investigations conducted in the past have indicated significant safety benefits of VSL due to speed reduction and speed homogenisation. VSL can also reduce vehicle emissions and road noise. There are a few researches conducted on impacts of VSL on the efficiency of motorway systems while they are quite limited on their scope. Combined effects of CRM and VSL on the performance of motorway systems are yet to be investigated.

A number of experimental and simulation studies conducted in the past to assess performance of RM strategies have verified a system-wide improvement in efficiency however some individuals might be disadvantaged as fair allocation of these improvements could not be guaranteed. Kotsialos and Papageorgiou (2001) found a partially conflicting relationship between equity and efficiency that is one rises as the other drops. Zhang and Levinson (2004) reported that the most efficient RM strategy is the least equitable one. They suggested that the system efficiency cannot be achieved without impacting on equity. However, Zhang and Shen (2010) found that the objectives of equity and efficiency can be obtained simultaneously and they do not necessarily conflict with each other. Gini coefficient proposed by Gini (1936) is a widely accepted measure in economic studies to analyse the degree of inequality in income distribution. The same can be used to measure inequities in motorway systems operating under different RM and VSL strategies.

In our previous attempt, we evaluated the effectiveness of ALINEA, HERO and VSL for a critical bottleneck section on Auckland Motorway State Highway 16 (Li and Ranjitkar, 2012). In this paper, we assessed ALINEA and HERO individually and in combination with VSL strategies for a critical bottleneck section of Auckland Motorway State Highway 1 using AIMSUN micro-simulation. We assessed their effectiveness to manage motorway traffic in terms of efficiency and equity to the road users. Total travel time and Gini coefficient are the two key performance indicators used to assess the efficiency and equity of the motorway system respectively. A review of literatures relevant to this study on LRM, CRM and VSL strategies and performance measures are presented in the following section; followed by a section to cover the details of modelling in AIMSUN micro-simulation software. Then the results are presented under three sub-headings namely system-wide performance, traffic conditions around merging area and equity aspect. Finally, the outcomes of this paper are summarized in the last section.

2. LITERATURE REVIEW

A great deal of research works was conducted in the last four decades to develop and implement a number of RM and VSL strategies. In the following paragraphs we present a review of some of those strategies relevant to this study.

2.1 LRM Strategies

Feed-forward and feedback are two basic principles used in the most of LRM strategies. ALINEA is a closed-loop feedback RM strategy, in which the metering rate is determined in proportion to the difference between the desired (also termed as critical) occupancy and observed downstream occupancy (Papageorgiou et al., 1991).

$$r(k) = r(k-1) + K_R[\hat{O} - O_{out}(k)] \tag{1}$$

where,

K_R(> 0) is a regulator parameter with a recommended value of 70 veh/h for the desired downstream occupancy also termed as critical occupancy ($\hat{O}$) that can vary from 0 to 100%;

O_{out} (k) is the observed downstream occupancy; and

R (k-1) is the metering rate at k-1 time step.

Equation (1) is known as an I-type (integral) regulator in the classical automatic control theory. This regulator would lead to $O_{out} = \hat{O}$ under stationary traffic conditions. Several variants of ALINEA strategy were proposed in literatures including UP-ALINEA, FL-ALINEA, UF-ALINEA and X-ALINEA/Q (Papageorgiou and Papamichail, 2007; Smaragdis and Papageorgiou 2003).A review of other LRM strategies can be found in Papageorgiou and Kotsialos (2002).

2.2 CRM Strategies

Rule-based CRM strategies employ a set of pre-defined heuristic rules, which activates related actions at individual on-ramps. HERO (Papamichail and Papageorgiou, 2008), ACCEZZ (Bogenerger, 2001), Zone (MnDOT, 2003), Bottleneck (Jacobson et al., 1989) and SWARM (Paesani et al., 1997) are some of the examples of rule-based CRM strategies. HERO incorporates ALINEA strategy at the local level in a group of on-ramps along a critical bottleneck section. At network level, when queue length at any on-ramp exceeds a pre-specified threshold value, HERO assigns it as a master on-ramp and then gradually employs successive upstream on-ramps to serve as slave ramp meters. This strategy exploits storage spaces of upstream on-ramps to improve the storage capacity of critical bottleneck section by maintaining minimum queue lengths at each of the slave on-ramps. The main objective is to prevent queue length at the master on-ramp from spilling back to the nearest intersection and to control the inflow onto the motorway to maintain an optimal mainline flow at the bottleneck.

The main advantages of HERO strategy as described by its developers are as follows:

- Make up the weaknesses of ALINEA strategy by coordinating local ramp meters in an appropriate way;
- No need for external disturbance prediction;
- Be generic (i.e. directly applicable to any motorway network) without further calibration;
- Approach the efficiency of complex optimal control;
- Be simple and transparent (rule-based).

2.3VSL Strategies

VSL can be used for two purposes: first, to homogenize flow to improve traffic safety (Smulders, 1990) and second to prevent traffic flow breakdown (Hegyi et al., 2005). Homogenization concept uses speed limits to reduce the speed differences between vehicles in order to achieve a safer and higher flow. The flow breakdown prevention approach can be used to prevent too high densities and to resolve shockwaves. Papageorigiou et al. (2008) evaluated the impact of VSL using the fundamental flow occupancy diagram. They concluded that there was no clear evidence of improvement in traffic efficiency using operational VSL systems.

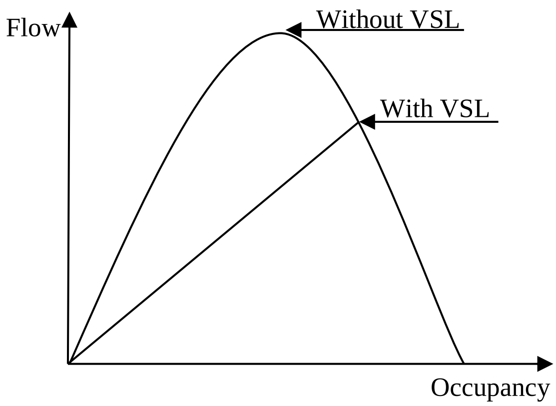

Figure 1. Fundamental diagram with and without VSL

Hegyi et al. (2005) proposed a model predictive control (MPC) system for optimal coordination of RM and VSL in combination. It was reported that RM strategies are effective only when traffic demands from on-ramps and mainline do not significantly exceed the downstream capacity. Lu et al. (2011) furthered this research using model predictive control approach taking into consideration mobility, safety, equity, and driver acceptance instead of just safety to claim suboptimal results from the overall system viewpoint. Caligris et al. (2007) refined METANET model considering two vehicle classes including cars and trucks to optimize VSL and RM strategies in combination. Abdel-Aty and Dhindsa (2007) investigated combined use of RM and VSL strategies to reduce the risk of crash and to improve operational parameters such as travel times and speeds.

2.4 Performance Measures

Total travel time (TTT) is the most commonly used to measure of effectiveness (MoE) used to measure the efficiency of motorway systems. A lower value of TTT represents lower delay and a higher outflow and therefore better traffic conditions. TTT is a system-wide efficiency measure, which can be measured in veh*h using the following formulation:

$$\mathrm{TTT} = \mathrm{T}\sum_{\mathrm{k}=1}^{\mathrm{K}}\sum_{\mathrm{i}=1}^{\mathrm{N}}\rho_i(\mathrm{k})\Delta_i \qquad (2)$$

where,

ρ_i is density of a segment i;
T is measurement duration;
Δi is the distance between two measured stations (i-1) and (i);
N is a number of measurement stations; and
K is time horizon.

Figure 2 illustrates the concept of Gini coefficient. The Lorenz curve (Lorenz 1905) shows the proportion of X receiving a given proportion of Y. While 100% of the population receives 100% of the resource, the more unfortunate 50% may only receive 25% of the total resource. The Gini coefficient corresponding to this Lorenz curve can be computed as $A_1/(A_1+A_2)$ in this graph. A zero value for Gini coefficient indicates perfect equality, while 1 indicates perfect inequality. Gini coefficient can be expressed as follows:

$$\mathrm{G} = \frac{1}{2\bar{\bar{\tau}}^2}\sum_{\mathrm{i}=1}^{\mathrm{n}}\sum_{\mathrm{j}=1}^{\mathrm{n}}\left|\tau_{\mathrm{i}} - \tau_{\mathrm{j}}\right| \qquad (3)$$

where,

G is the Gini coefficient;
$\bar{\tau}$ is the average delay time of all on-ramps;
i and j are the i^{th} and j^{th} on-ramp;
τ_i is the delay time on the i^{th} on-ramp; and
n is the number of on-ramps.

3. MODELING IN AIMSUN

Traffic simulation is a promising tool to assess the effectiveness of different ITS measures before implementing them in the field. We developed an Application Programming Interface (API) in AIMSUN micro-simulation software to implement and verify the performance of

HERO strategy for a critical section of Auckland Motorway. The working principle of the HERO algorithm as proposed by its developers can be outlined as follows:

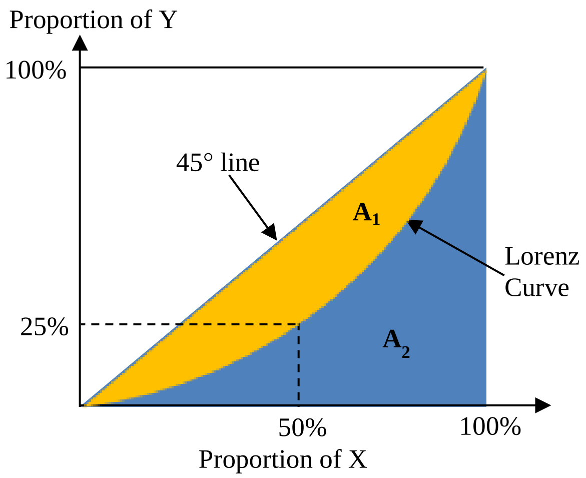

Figure 2. Sketch map of Lorenz curve (modified from Lorenz, 1905)

1) At each control time interval T_c, HERO controllers receive from local controllers the information on current on-ramp queue length and traffic states of the mainline; based on which it decides a possible coordination action.
2) Whenever a relative on-ramp queue length exceeds a pre-specified activation threshold value, HERO control strategy is activated and the respective on-ramp is turned as a "master". The "master" gradually employs successive upstream on-ramps as "slaves".
3) HERO assigns minimum queue lengths to the successive upstream on-ramps to avoid long queues at the "master" on-ramp. The minimum queue length is computed as follows:

$$W_{min}(k) = \frac{W_{max}(k) \times Sum\_W(i)}{Sum\_W_{max}(i)} \tag{4}$$

where,

W_{max} (k) is the maximum admissible queue length of the respective on-ramp;
Sum_W (i) is a sum of current queue lengths at each on-ramps within the coordination control string; and
Sum_W_{max} (i) is a sum of the maximum admissible queue lengths at each on-ramps within the coordination control string.

4) For each T_c, HERO updates the minimum queue lengths at each "slave" on-ramps so that the relative queue lengths at each on-ramps can be kept close to each other.
5) HERO gets deactivated when the relative queue length of the "master" on-ramp drops below the deactivation threshold value.

Figure 3 presents a flowchart of HERO strategy, where W(i) is an observed queue length for an on-ramp i. act (j) and deact (j) are activation and deactivation threshold values respectively. As shown in this figure, HERO works in three different steps. The first step is detection of master on-ramp is followed by the second step to define dissolution of the coordination string. In the third and final step, minimum queue lengths for each "slave" on-ramps are determined using equation (4) formulation.

Figure 4 illustrates HERO control process that we used in AIMSUN software. ALINEA ramp meters installed at each on-ramp receive occupancy and flow data from AIMSUN model and calculate their individual metering rates locally and autonomously. Once HERO control strategy is activated due to detection of "master" on-ramp, the current queue lengths data from each on-ramp are transmitted to HERO API. Based on this information, HERO API determines and assigns minimum queue lengths at each "slave" on-ramps. The related control actions and minimum queue lengths are updated at each control time interval T_c. It shall be noted that queue lengths at each on-ramps (aggregating all vehicle types) can be automatically obtained in AIMSUN. However, HERO coordination software (Papamichail and Papageorgiou, 2008) employs a queue estimation module proposed by Vigos et al. (2008) which is a Kalman filter based estimator. The minimum queue length determined by HERO controller was enforced by implementing the minimum metering rate at each local controller.

For VSL controller, we employed a flow-based algorithm as used in M25 VSL system in England. All control actions related to VSL are realized in AIMSUN using strategies function. During each control time interval T_c, traffic volume information received from the mainline detectors immediately upstream side of the on-ramp is compared against activation threshold value. When the relative flows reach or exceed the activation threshold value, then certain "triggers" will be launched and related VSL "strategies" which are pre-defined in "strategies" function will be activated. "Speed change" function exerts speed limits on the respective control segments. After testing several driver compliance rates including 50%, 80% and 100%, we found only nominal differences between them. Hence in this study, we presented only the results with 100% driver compliance (that is a case of strictly enforced VSL). Figure 5 presents a conceptual diagram of VSL implementation at each on-ramp.

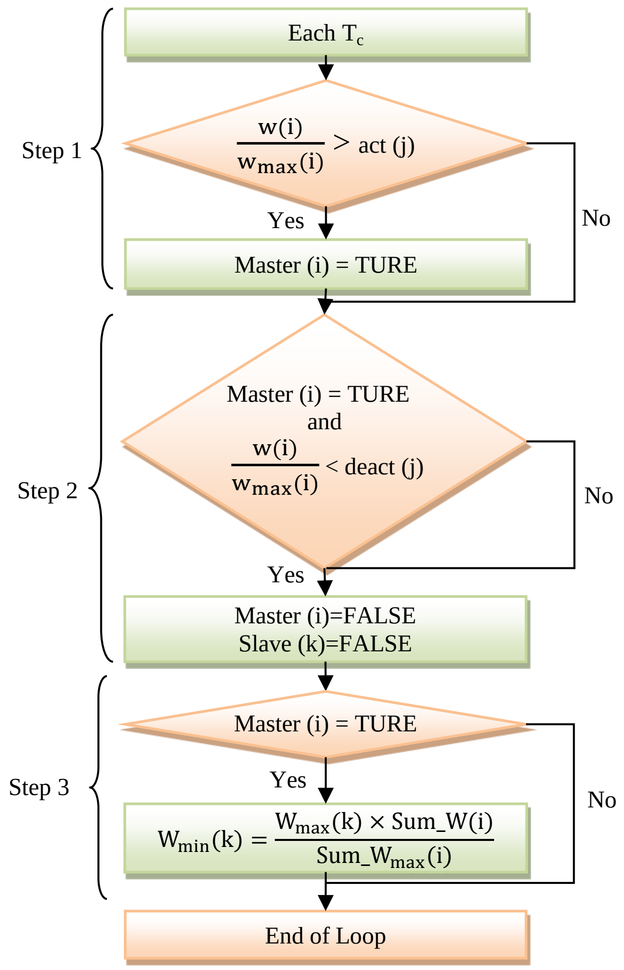

Figure 3. Flowchart of HERO strategy

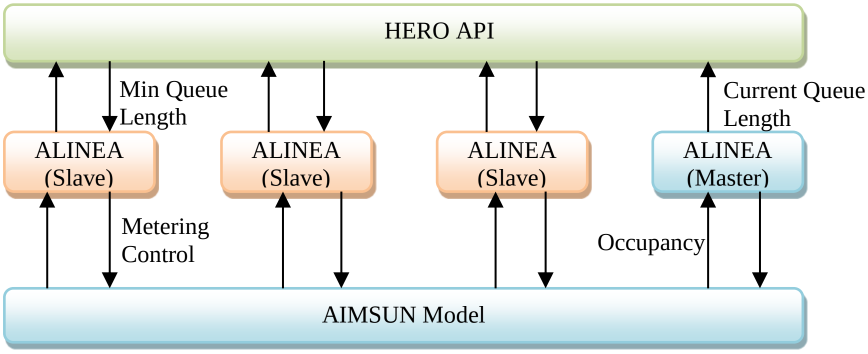

Figure 4. Implementation of HERO strategy in AIMSUN

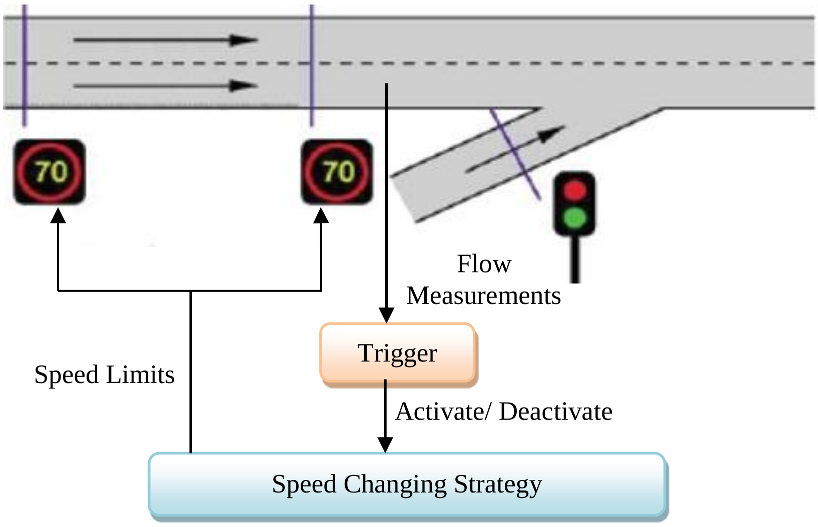

Figure 5. VSL implementation at each on-ramp (Note: *strategy* and *trigger* are internal functions of AIMSUM)

A critical bottleneck section on State Highway 1 of Auckland Motorway connecting Central Auckland with Northern Auckland was selected for this study. Figure 6 presents a layout of the study section, which has 5 on-ramps and 4 off-ramps in a direction towards Auckland city centre. Here O_1 represents on-ramp from Esmonde Road while O_5 represents on-ramp from Greville Road. 30% and 15% of maximum queue length were used as activation and deactivation threshold values respectively for the HERO control strategy. The network data used in this study was provided by New Zealand Transport Agency (NZTA) which includes loop detector measurements from the on-ramps, off-ramps and mainline accumulated over a 30 seconds time period. The data collected on Monday, 12^{th} March, 2012 was used to calibrate the simulation model while the data collected on Friday 9^{th} March 2012 was used to validate the simulation model.

GEH statistic is commonly used for calibration and validation of micro-simulation model (Dowling et al., 2004). The same was used in this study also to calibrate and validate the model based flow data collected from 14 loop detectors. GEH values remained below 5 for most of the cases for calibration as well as validation (more than 85% of the observed detectors are considered acceptable) and hence the model was used for further analysis to testing of different scenarios presented in the next section.

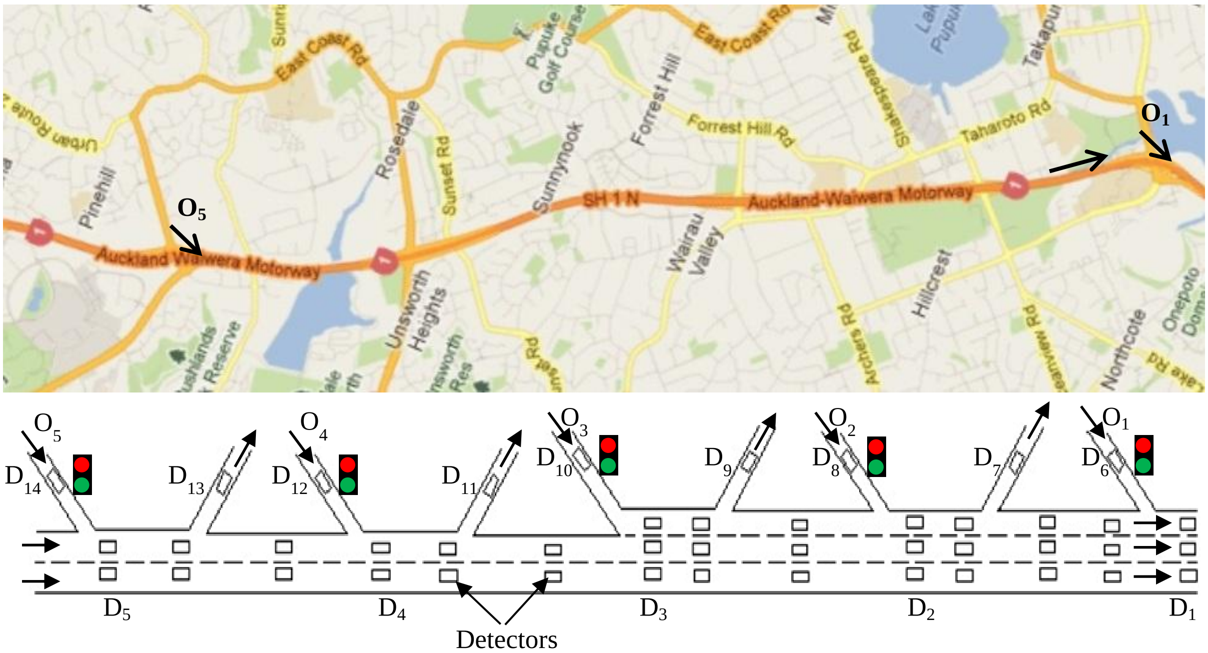

Figure 6. Layout of study area

4. RESULTS

In AIMSUN, we systematically tested six different control scenarios for the study section including no control scenario, only VSL, ALINEA, ALINEA+VSL, HERO and HERO+VSL. Here “no control” scenario is used as a reference to measure improvements achieved by other control scenarios in terms of efficiency and equity of the motorway system. ALINEA and HERO were assessed individually and in combination with the VSL strategy.

4.1 System-wide Performance

Table 1 presents TTT (a measure of efficiency) computed for the entire study area of the motorway network under different control scenarios. The TTT computed using only VSL strategy (1658 veh*h) when compared with no control scenario (1669 veh*h) improvement is not that significant (less than 1%). ALINEA strategy individually recorded over 12% improvement in TTT when compared with no control scenario. HERO strategy individually recorded an improvement close to 18% compared with no control scenario. VSL contributed positively to improve efficiency of the motorway system when combined with ALINEA and HERO though such improvement remained far from being significant. Figure 7 presents a time series of total travel time (TTT) for the entire study section under different control scenarios. It can be observed that improvements contributed by ALINEA and HERO strategies are mainly during the peak periods in this case from around 6:45 to 8:00 AM after which they produce higher TTT values compared to no control scenario representing less efficient system.

We conducted F-test and T-test to check how significant the differences in the TTT values are under different control scenarios and the results are presented in Table 2. On F-test results, the cells highlighted with a dark background represent cases of significant difference in the variance and was treated the same when computing the T-test results. On T-test results, the cells highlighted with a dark background represent cases of significant difference in the mean representing significant improvement in TTT when compared with the other scenarios. For cases of VSL individually or in combination with ALINEA and HERO the improvement is not that significant. Based on these results, it can be concluded that the network controlled by HERO outperforms the one controlled by ALINEA. Furthermore, HERO combined with VSL has potential to improve the efficiency of the motorway system significantly though individual impact of VSL is not that significant.

Table 1. Total travel time for different scenarios

	No control	VSL		ALINEA		ALINEA+VSL		HERO		HERO+VSL	
		Value	% Impr.*	Value	%Impr.*	Value	% Impr.*	Value	% Impr*	Value	% Impr.*
TTT (veh*h)	1669	1658	0.66	1461	12.46	1458	12.64	1370	17.91	1363	18.33

* Compared to No-control option

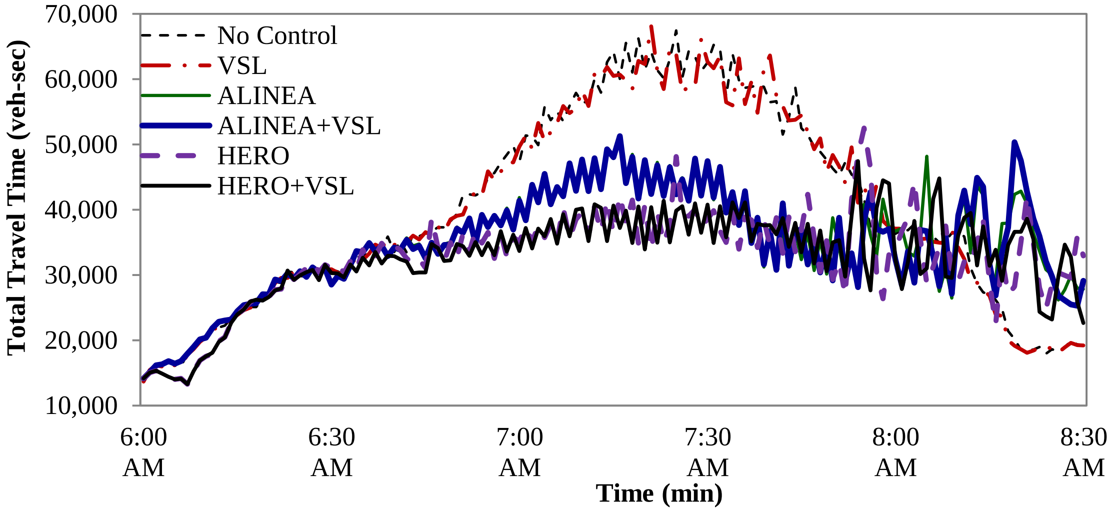

Figure 7. Time series of TTT under different control scenarios

Table 2. Results of F-test and T-test for TTT under different scenarios

		No control	VSL	ALINEA	ALINEA+VSL	HERO	HERO+VSL
		F-Test Results					
No control	T-Test Results		1.03	3.51	3.40	4.04	4.61
VSL		1.70		3.42	3.32	4.29	4.49
ALINEA		5.75	5.44		1.03	1.25	1.31
ALINEA+VSL		5.68	5.38	0.76		1.29	1.35
HERO		7.60	7.41	4.86	4.64		1.05
HERO+VSL		7.86	7.63	5.53	5.19	0.42	

F critical = varies between 1.34
T critical = 1.97
NOTE: Grey background is used for the values exceeding critical values indicating significant difference.

4.2 Traffic Conditions around Merging Areas

Figure 8 presents speed contour plots under different control scenarios. It can be observed that traffic congestion mainly occurs on the first three merging areas in no-control and only VSL scenarios. The red and yellow spots (representing slow moving traffic) have reduced significantly for ALINEA and ALINEA+VSL scenarios when compared with no control and only VSL scenarios, representing significant improvement in speed environment near the merging areas. A minimal number of red and yellow spots are left in HERO and HERO+VSL scenarios when compared with ALINEA and ALINEA+VSL scenarios representing further improvement in speed environment contributing to even lower TTT. Table 3 presents mean speed downstream (near the merging areas) and average on-ramp delay. There is not much difference in the average downstream speed measured for no control and only VSL scenarios

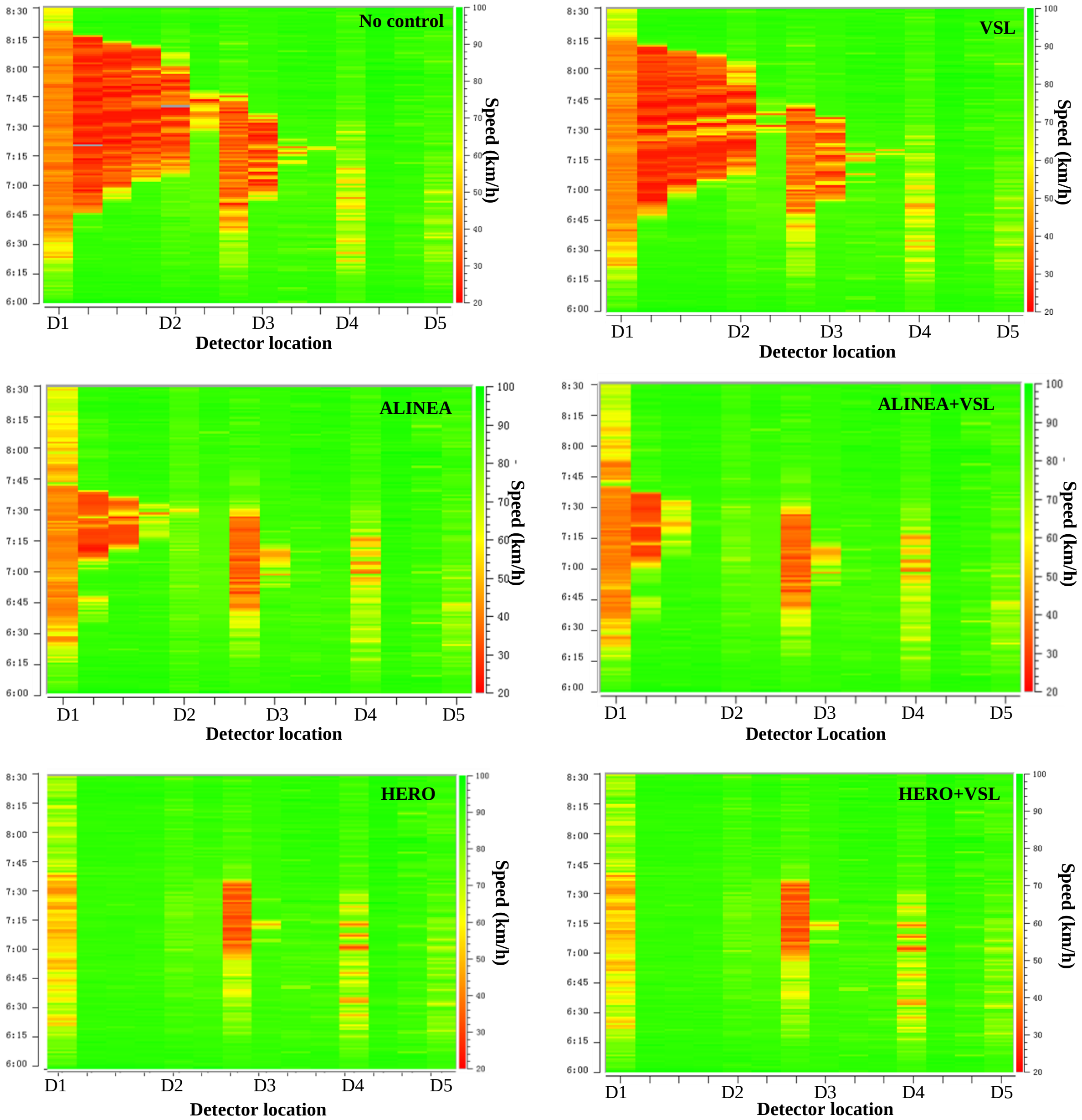

Figure 8. Speed contour plots under different control scenarios

near five on-ramps locations. ALINEA and HERO have improved significantly the average downstream speed near the first three on-ramps however the average downstream speed has decreased slightly near the last two on-ramps. The average delay at all on-ramps has increased significantly for all scenarios except only VSL scenario when compared with no control scenario.

Figure 9 presents density contour plots under different control scenarios. HERO+VSL gives the best results compared with all other scenarios while HERO individually also peformed quite well with lower densities around the merging areas, which represents an efficient system. Figure 10 presents queue lengthprofile at the five on-ramps under different control scenarios. For the first two scenarios namely no-control and only VSL scenarios, most of the delays occur near on-ramps O_1 and O_2. This is mainly due to the formation of bottleneck on the mainline near the on-ramp O_1 due to heavy traffic demand and then propagation of the congestion to the immediate upstream on-ramp location, which is O_2. For all other scenarios, there is significant increase in queue length at the on-ramps. This is obviously because of metering applied to the on-ramps creating longer queues and longer delays under those scenarios. Both of HERO scenarios create longer queue lengths and delays at the last four on-ramps (slaves) compared with ALINEA scenarios while it has slightly improved on the average on-ramp delay for the master on-ramp O_1.

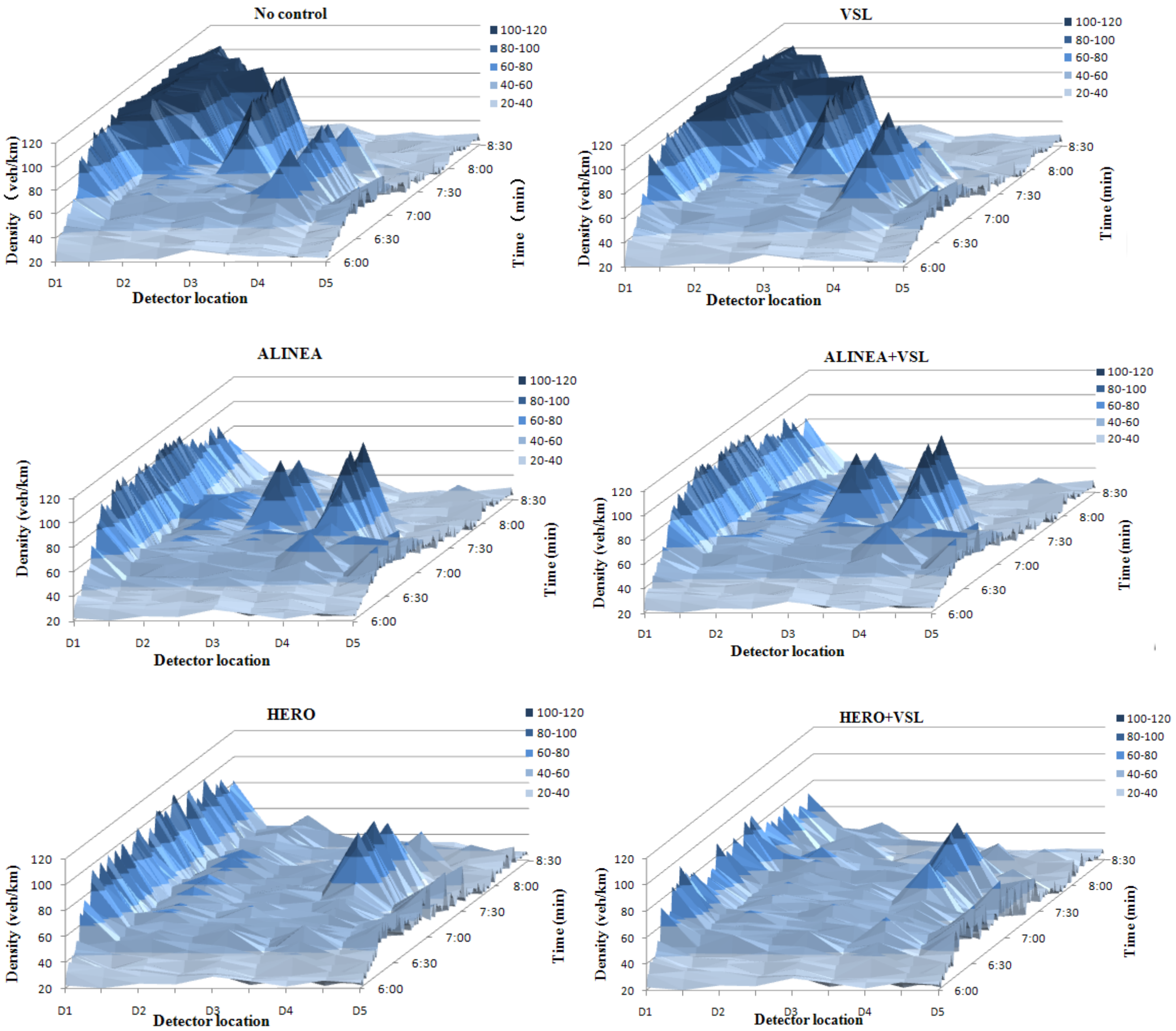

Figure 9. Density contour plots under different control scenarios

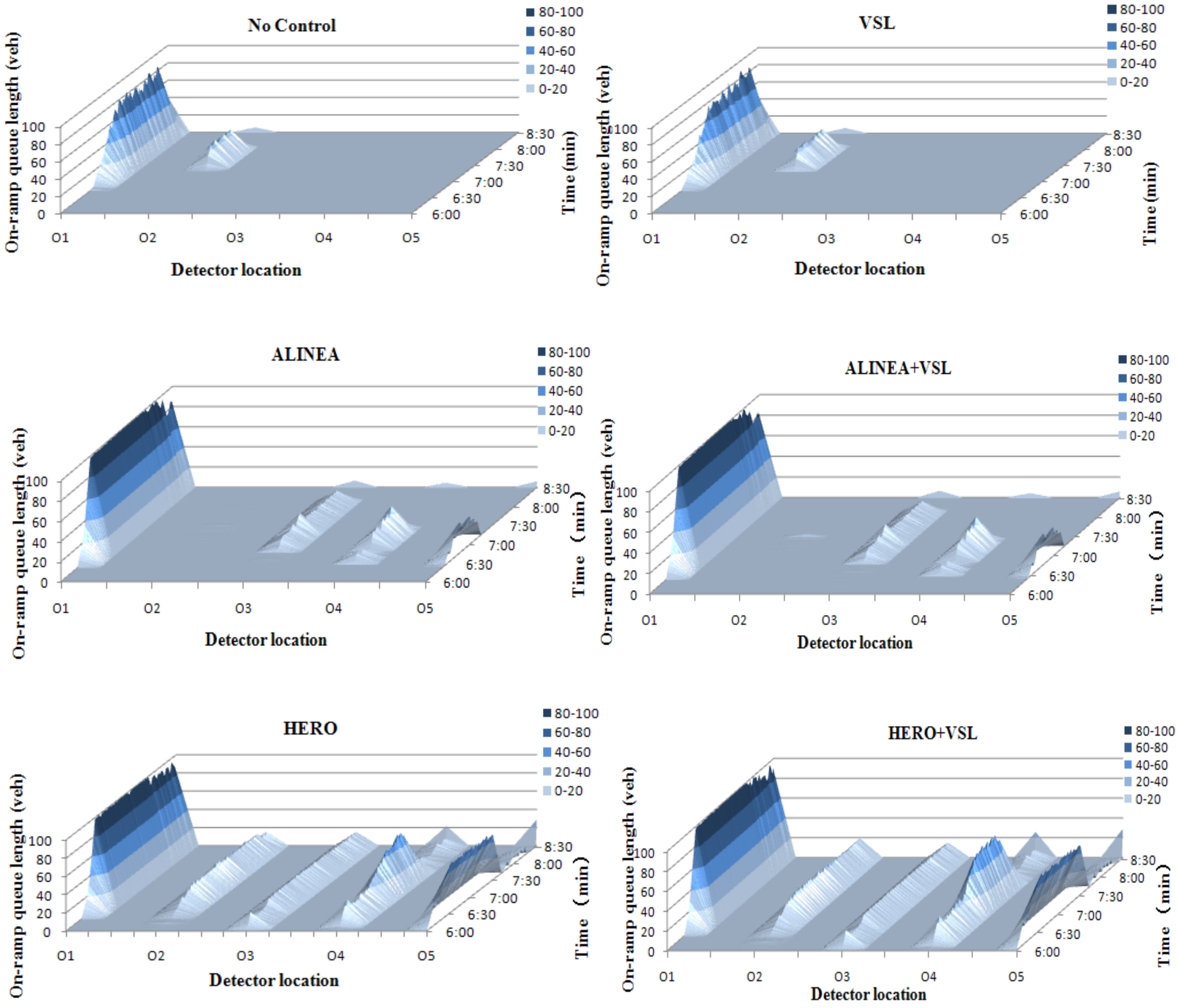

Figure 10. On-ramp queue length profile under different control scenarios

4.3 Equity Aspect

As observed in Table 3 and Figure 10, huge delay occurs at the on-ramp O_1. It might be unfair for the drivers using the on-ramp O_1 to experience such an excessively long delay. Figure 11 presents a plot of Gini coefficient values under different control scenarios as a measure of inequalities among motorway users. ALINEA and ALINEA+VSL have produced significantly higher Gini coefficient values when compared with no control and only VSL scenarios; representing less equitable systems. While HERO and HERO+VSL produced relatively lower Gini coefficient values compared with all other scenarios representing the most equitable systems. This improved equity performance of HERO strategy can be attributed the concept to distribute queue lengths to the successive “slave” on-ramps, which also helps to distributes delay among the on-ramps. There is only marginal difference between the performances of HERO and HERO+VSL where the former performed better than latter in terms of equity of the system.

Table 3. Mean speed downstream (near merging areas) and average on-ramp delay

		No control	VSL		ALINEA		ALINEA+VSL		HERO		HERO+VSL	
		Value	Value	% Impr.*	Value	% Impr.*	Value	% Impr.*	Value	% Impr.*	Value	% Impr.*
Mean speed downstream (km/h)	O_1	50.0	50.4	0.8	65.3	30.5	66.0	31.9	70.8	41.5	71.9	43.8
	O_2	68.7	70.3	2.3	88.0	28.1	88.3	28.4	88.3	28.5	88.4	28.6
	O_3	75.7	77.3	2.1	89.7	18.5	91.0	20.2	91.3	20.6	91.2	20.5
	O_4	80.0	80.0	0.0	79.0	-1.2	79.5	-0.5	79.7	-0.4	78.3	-2.1
	O_5	86.0	86.1	0.1	85.6	-0.5	85.3	-0.8	84.6	-1.6	84.7	-1.6
Average on-ramp delay (secs)	O_1	289.0	286.1		1326.2		1319.4		1278.5		1245.0	
	O_2	55.7	56.6		0.8		1.1		126.3		134.0	
	O_3	0.3	0.3		39.1		39.1		100.6		99.5	
	O_4	0.1	0.1		38.1		38.1		204.7		242.5	
	O_5	0.1	0.1		58.4		58.4		369.6		383.6	

* Compared to No-control option

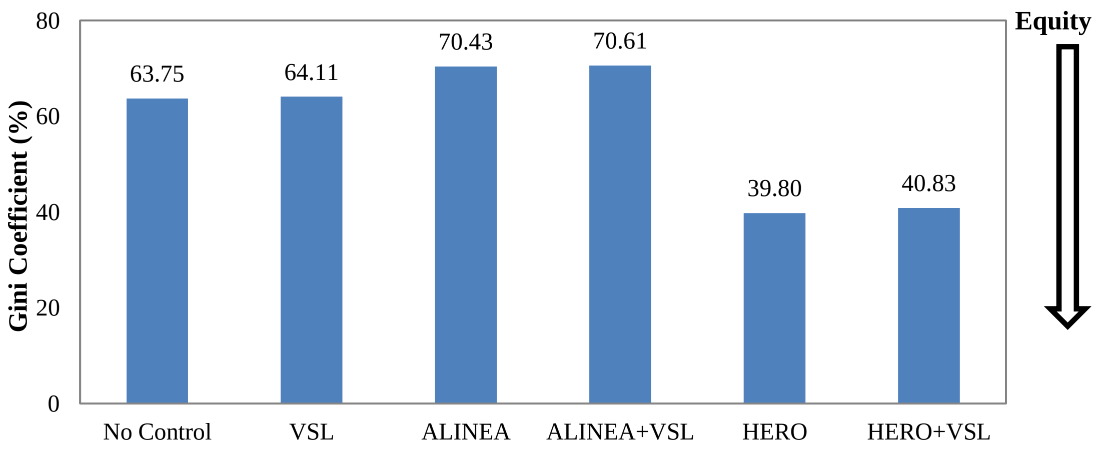

Figure 11. Gini coefficient values under different control scenarios

Following conclusions can be drawn based on the results presented in the previous section:

- HERO combined with VSL control strategy has outperformed all other control strategies including no control, only VSL, ALINEA, ALINEA+VSL and only HERO control strategies in terms of the efficiency as well as the equity of the motorway system.
- The impact of VSL was not that significant to improve either efficiency or equity of the motorway systems.
- HERO strategy assigns queue lengths in a more balanced way among a group of successive on-ramps, which might have contributed to improve the equity for the motorway system significantly when compared with other strategies tested in this paper.

It shall be noted that these results cannot be generalized as they are based on a particular section of Auckland motorway modelled in AIMSUN micro-simulation. The model can have its own limitations to represent real-world traffic conditions. It is recommended to conduct similar investigation under a range of different traffic conditions and for a range of motorway networks before generalizing any such results.

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