New Horizontal Equity Measure for Ramp Meters

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Ramp metering is a control technology used to manage the flow of traffic entering motorways and freeways, with the primary aim of minimizing congestion on the main thoroughfare. This technique has been studied and implemented globally since the 1960s. It has been shown that ramp meters improve the overall efficiency of the system; however, the distribution of the benefits and costs across users has been questioned, and this is one of the main constraints on user acceptance of the ramp metering system. The typical methodology used in the literature is to assume that the most equitable condition is when all on-ramps have the same delay across space or time. This research developed a new definition of horizontal equity for ramp meters and a proposed method for calculating it. A hypothetical microsimulation model was developed on the basis of a motorway in Sydney, Australia, and used as the platform to demonstrate how the proposed equity definition can be evaluated. To assist in the interpretation, two configurations of a ramp metering algorithm were simulated and compared. Finally, the typical equality measure used in the literature was calculated for the same scenarios and compared with the proposed equity measure. The results showed that these two measures can favor scenarios. A qualitative discussion of the expected benefits of the proposed equity measure is offered. Those expected benefits are an easy-to-communicate means of justifying the metering rates for user acceptance (rates that are arguably fairer, compared with the typical equality measure); a measure that is complementary to integration with other intelligent transportation system technology such as tolled bypass lanes; and ease of incorporation in the long-term traffic management plan.

Equity, as a representation of justice or fairness, refers to the distribution of impacts (benefits and costs) and whether that distribution is considered appropriate. Road authorities consider these distributions as part of the evaluation process of transport projects and as essential for the support of public officials and the general public (*1–4*). How equity is defined and measured can significantly affect analysis results.

There are three fundamental classifications of equity: (*a*) equality or egalitarian, where each person is assigned the same amount of benefit; (*b*) horizontal equity (also called market equity), which relies on the idea that you should get what you pay for—thus, benefits and costs are distributed on the basis of the amount of benefits and costs that are received from the individual; and (*c*) vertical equity, where benefits are distributed on the basis of the needs or socioeconomic status of the individual. However, when evaluating the equity of a system, many other aspects also must be considered, including the measure of benefits and costs, the aggregation method to obtain measurements, the categories of people, the definition of the base case, and the formulation used to summarize the distribution (*5*).

Ramp meters (RMs) have been in use for more than 50 years. The purpose of an RM is to regulate and reduce the flow of traffic onto a freeway when congested traffic conditions are emerging, resulting in the reduction or avoidance of congestion along the freeway. Ramp metering is beneficial because analysis has shown that it takes longer for congested traffic to clear in comparison with the delay enforced at the on-ramps (*6*). Although the total travel time of the freeway system is improved, some drivers may receive substantial benefits at the expense of others, resulting in public objection to RMs and thus limiting the expansion of RM systems (*7*). Such challenges faced by policy makers who seek to implement RMs within the regional transport system served as the motivation for this study.

The main contributions of this paper are a new horizontal definition of equity for evaluating RMs and a methodology for calculating and summarizing the proposed equity definition. The proposed equity measure requires tracking vehicles by utilizing the advancements in vehicle tracking technology. Thus, the contribution of an on-ramp to the congestion on a freeway bottleneck can be calculated with increased precision. In addition, the following factors are incorporated: dynamic demand for each on-ramp (i.e., changes to the congestion contributions from an on-ramp over time), the travel time required to reach a bottleneck (especially for bottlenecks located at long distances from the on-ramp), the amount of time spent in a bottleneck (i.e., the duration of a vehicle's contribution to a bottleneck), and the consideration of on-ramp delays for motorists not contributing to the congested bottleneck or bottlenecks. The proposed methodology can be built on top of most heuristic RM algorithms; thus, it builds on the existing body of knowledge and is complementary with most RM systems that are in operation. In this research, the determination of assigning a vehicle to a congested bottleneck was achieved using the outputs of the HERO RM algorithm. Although the focus was on defining and evaluating the proposed equity measure, general implementation ideas are also discussed. If implemented, the proposed equity measure could be beneficial for user acceptance and long-term demand management, as well as being complementary to other intelligent transportation system technology, such as toll bypass lanes.

The following section presents a review of the literature on RM equity, followed by a description of the methodology for evaluating the proposed equity measure. The application of the proposed methodology in a microsimulation model with the HERO RM algorithm is described next. Two configurations of the RM algorithm are applied to allow for the interpretation of the proposed equity measure, and the proposed equity measure is compared against the typical equality definition. A discussion of the results as well as the additional

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benefits if the proposed equity measure is implemented follows that comparison.

LITERATURE REVIEW

The underlying reason for evaluating equity for ramp metering has been to increase user acceptance. Reviews of the literature state that public perception of an inequitable system (regardless of the system efficiency) ultimately influences the success of the RM initiative (*8, 9*). The most prominent example is the Twin Cities of Minneapolis and Saint Paul, Minnesota, where the "Ramp Metering Holiday" Bill that was passed by the state legislature included switching ramp metering off for a period of eight weeks in late 2000 (*10*). The opposition to RMs that led to this bill was quoted in the media as follows (*11*): "I'd be driving to the Capitol at 65 mph, and I'd look at the side of the road and there would be 20 to 40 cars lined up, all waiting, while there was plenty of room on the highway for everybody. I thought to myself, the first person who stops, what . . . is he thinking?"

Levinson has highlighted the issue with the existing transport appraisal process, where the main concern is the net benefit of the system (*12*). However, a project with a net benefit may be politically troublesome if users receiving the costs of the system are concentrated, resulting in a loud opposing force. This scenario particularly applies to RM projects, which tend to apply the most restrictive metering to the on-ramps near the bottlenecks (i.e., delays are varied across on-ramps) (*13*). The typical result is that users entering the highway closer to the city tend to experience more on-ramp delay, while those living farther away will benefit the most as both the on-ramp and mainline delays are reduced relatively more in their favor (*9, 14*). This is a possible explanation for why there is a positive correlation between total travel time and the level of positive support toward ramp metering (*15*).

To understand the main objections to RMs, previous surveys on the perceptions of users in relation to RMs were examined. Three main objections were observed. One, RMs are seen to favor some users at the expense of others, depending on the on-ramp used. One of the primary reasons for public opposition to RMs is because the system is believed to disadvantage users who are traveling on short trips without alternative routes and who are living near the city centers. This is because freeway systems near the city centers are more likely to be congested, triggering the traffic-responsive RMs to impose higher delays (*9, 15*).

Two, there is a tendency to accept RMs only when congestion is seen directly by the users (*11, 15, 16*). One survey, comprising 68 respondents, suggested that the main objections were that traffic flow is unnaturally restricted because of RMs and users questioned whether RMs were improving their total travel time (*17*). To the public, RMs are often seen as a constraint on a roadway that is normally associated with a high degree of freedom (*7*). Several road authorities have acknowledged that sufficient effort in public relations campaigns to soften the initial impact of metering and periodically reminding the public of the benefits of RM is beneficial to gain public and political support (*7*).

Three, a loss in user confidence in the RM system occurs when long on-ramp delays (e.g., greater than 20 min) are experienced (*18*). The issue is that the total travel time savings may not be recognized by an individual motorist, but a 3-min wait at an on-ramp is easily recognized. Users' perceptions of travel time differ depending on the context (e.g., congested, stop-and-go, on-ramp delay, the length of the trip). Survey results on the transformation models converting different parts of the journey into perceived travel times are not conclusive (*14, 19*).

Other papers also highlight the need to consider equity before political problems appear (*13, 20*). FHWA has developed a promotional video for the general public and public officials called "Ramp Metering: Signal for Success" (*21*). The video states that "many are concerned that ramp metering won't be equitable" and that "careful monitoring of freeway flow and analysis of freeway capacity can ensure equitable access for all travelers." This highlights the necessity for proponents of RM systems to identify, track, and address the equity issue.

The definitions of equity used to evaluate RMs are varied across the literature. Table 1 summarizes these definitions, using the components of equity (i.e., the column headings) as described by Litman (*5*). The main focus of these studies is on evaluating equity of different RM algorithms, incorporating equity within the RM strategy, or assessing the trade-off between efficiency and equity (*8, 22, 23*). Regardless of the type of study, a number of equity definitions have been used.

Table 1 indicates that the typical interpretation of an equitable RM relies on an equality or egalitarian definition of equity (*8, 10, 18–20, 22, 24–27*). More specifically, an RM system is typically considered equitable when equal delay is experienced across all on-ramps. More, the spatial equity of on-ramp delays is normally considered (i.e., an on-ramp delay is averaged for the duration of the study period), and summarized using the Gini coefficient. This definition of equity—the typical definition of equality (TDE)—aims to assign the same on-ramp delay regardless of where a motorist enters the motorway and does not consider a motorist's route choice. For example, an on-ramp with motorists who travel only a short distance on the motorway and do not contribute to any bottlenecks is presumed to require the same on-ramp delay as another on-ramp with motorists that are traveling through a number of bottlenecks. Given that RM systems typically set the metering rate in response to the congestion along the freeway bottlenecks (*9, 28–30*), it is only fair that the motorists who contribute to the bottleneck should be assigned the resulting on-ramp delays; the other motorists, who do not contribute to the bottleneck, should not be assigned any on-ramp delay.

Road agencies have used a number of practical strategies to address the public acceptance issue. In Detroit, Michigan, RMs were initially applied in the outbound direction only, as residents living closer to the city center argued that suburban commuters were obtaining all the benefits at their expense (*20*). In Minnesota, the metering algorithm was modified to limit ramp delays to less than 4 min (*15*). In Seattle, Washington, the RM algorithm was designed to allow a more restrictive metering rate at upstream on-ramps (*9*). In Milwaukee, Wisconsin, only the on-ramps that contributed to the freeway bottlenecks were considered for metering, and the metering rates were designed to allow for comparable flow reduction across all metered on-ramps (*7*).

DEVELOPMENT OF HORIZONTAL EQUITY METHODOLOGY

The purpose of this study was to address the inequity issues that are not captured using the TDE by proposing a new horizontal equity definition and providing a methodology for calculating it. A hypothetical microsimulation model, developed on the basis of a motorway in Sydney, Australia, was used as the platform to show how the proposed equity definition could be calculated. The HERO RM algorithm was simulated using two configurations in order to

TABLE 1 Definitions of RM Equity

Study	Type of Equity	Impacts	Measurement	Base	Formulation	Analysis Platform
Benmohamed and Meerkov (*24*)	Max.–min. fair (horizontal based on the same flow rate from each O-D pair using the same bottleneck).	Freeway capacity is distributed evenly among O-D pairs	Per O-D pair	None	Control system (not evaluation)	Simulation: macroscopic model
Yafeng et al. (*20*)	Mainline and on-ramp relative change in TT should be the same (horizontal based on TT changes in shorter trips more sensitive).	Travel time ratio = TT no RM/TT with RM	Per vehicle	No RM	Evaluation standard Gini	Simulation: paramics
Kotsialos and Papageorgiou (*22*)	On-ramp and mainline TT should be the same for each time step.	TT at on-ramp and 6.5 km of the mainline	Per on-ramp per time step	No Base—direct calculation adjustment	Variance	Simulation: AMOC using macroscopic model
Zhang and Levinson (*18*)	On-ramp delay to be the same for a set of coordinated on-ramps sharing a bottleneck; it's assumed the larger the number of coordinated on-ramps, the higher the equity (egalitarian).	On-ramp delay is weighted according to length of wait	On-ramp delay per vehicle	No RM	Control system (BEEX)	Simulation: AIMSUN2
Levinson and Zhang (*10*)	Average travel time to be the same across O-D pairs and time intervals (comprising on-ramp delay and mainline travel time, egalitarian).	Average on-ramp delay and mainline speeds per time interval converted to travel time	On-ramp and travel mainline time per vehicle	No RM is assumed to have zero ramp delay for all drivers	Evaluation standard Gini	Before–after study: weeks RMs were disabled
Winyoopadit (*25*)	All vehicles should experience the same speed, TT/vkt and delay/vkt (mobility measures are only considered for the ramps and mainline, egalitarian).	Speed, TT/vkt, delay/vkt	Per vehicle	No base—direct calculation	Evaluation standard Gini	Simulation: AIMSUN NG
Meng and Khoo (*19*)	Min. and max. on-ramp delay to be the same across all on-ramps assigned to a (neighborhood) group.	On-ramp delays	Per on-ramp group	None	Optimum control system, Pareto optimization (not evaluation)	Simulation: modified-cell-transmission-model
Armstrong (*8*)	Minimize SD in on-ramp delays.	On-ramp delay	Per vehicle	ALINEA	Included in objective function	Simulation: Vissim
Khoo (*26*)	Min. and max. on-ramp delay to be the same across all on-ramps assigned to a (neighborhood) group.	On-ramp delays	Per on-ramp group	None	Optimum control system, genetic algorithm (not evaluation)	Simulation: modified-cell-transmission-model
Li and Ranjitkar (*27*)	Delays at each on-ramp should be the same (average delay, egalitarian).	Average on-ramp delay	Per on-ramp	No base—direct calculation	Evaluation standard Gini	Simulation: AIMSUN

NOTE: O-D = origin–destination; TT = travel time; AMOC = Advanced Motorway Optimal Control; BEEX = balanced efficiency and equity strategies with equity coordination factor *X*; vkt = vehicle kilometers traveled; ALINEA = Asservissement Linéaire d'Entrée Autoroutière.

compare them and thus allow for the interpretation of the results. Finally, the results were used to compare the proposed equity definition against the TDE.

Definition of Proposed Horizontal Equity

The aim of the proposed horizontal definition of equity is to ensure that the metering delay incurred for each vehicle at an on-ramp is directly associated with the total delay that the vehicle causes because of its driver's route choice along the freeway. A simplified and intuitive definition is: motorists are assigned a metering delay on the basis of the level of congestion they cause.

The formal definition is this: the total metering delay (i.e., across all on-ramps) that was triggered by a freeway bottleneck during a predefined time-slice should be distributed among each on-ramp on the basis of the number of vehicles from each on-ramp that reached the congested bottleneck, divided by the total number of vehicles present at the congested bottleneck. Finally, the on-ramp delays are reduced (and redistributed iteratively) on the basis of the proportion of other vehicles present at the on-ramp that did not reach the congested bottleneck.

Two versions of the proposed horizontal equity are calculated in this study. The first is referred to as the ideal horizontal equity (IHE), which considers all entry points onto the freeway, including the uncontrolled on-ramps and the mainline itself. The second version is referred to as the practical horizontal equity (PHE), which considers that some entry points cannot be controlled; thus, the equitable delays are distributed only among the controlled entry points. The PHE in this study is the same as IHE, except that traffic from the uncontrolled entry points onto the freeway are excluded from the analysis. The PHE approach can be expanded further to incorporate other practical considerations, such as maximum waiting time (typically set by the road authority to address user confidence and compliance), bypass lanes, or the consideration of combining RMs with other freeway management measures such as tolling.

Calculation of Proposed Horizontal Equity

The methodology for calculating the IHE is provided in this section. The output of the methodology is the reallocation of the metering delays according to the IHE definition (i.e., the IHE metering delays that should have been applied to each on-ramp at each time-slice).

Initially, both time and space are discretized. The study period is divided by the sample time-slice (T) (in this study $T = 240$ s) indexed using the integer $K \geq 0$. The freeway is divided into segments (S), defined as an index associated with a stretch of the freeway between any two adjacent ramps (i.e., on- or off-ramps). By combining the discretized definitions of time and space, it is possible to refer to specific events. Thus, events at the freeway segment S during time-slice K are denoted as $S(K)$. An entry point (E) is defined as an index referring to a geographical location at which vehicles can enter the freeway (e.g., an on-ramp). Thus, events at entry point E during time-slice D are denoted as $E(D)$ [D is an index similar to K; it has been used to distinguish between departure-time (i.e., D = entry-time to the freeway) and time of travel on the freeway (i.e., K)].

Assuming that the trajectory of all vehicles during the study period is available, the total number of vehicles present on segment $S(K)$ that entered the freeway at $E(D)$ can be calculated, and is denoted as $V_{E(D),S(K)}$, where $V_{E(D)}$ is the total number of vehicles that enter the freeway at $E(D)$. Using these flow variables, the following three variables can be computed to evaluate the IHE delay at $E(D)$:

1. The proportion (P) of the total number of vehicles traveling on the segment $S(K)$ that originated from the entry point $E(D)$:

$$P1_{E(D),S(K)} = \frac{V_{E(D),S(K)}}{\sum_{E} \sum_{D} V_{E(D),S(K)}} \tag{1}$$

2. The proportion of the total number of vehicles that enter the freeway from the entry point $E(D)$ that eventually reach the segment $S(K)$. All the traffic entering the freeway from the same entry point $E(D)$ will receive the same delay regardless of route. Thus, this variable is required to reduce the on-ramp delay if the on-ramp contains vehicles that do not contribute to the freeway congestion.

$$P2_{E(D),S(K)} = \frac{V_{E(D),S(K)}}{V_{E(D)}} \tag{2}$$

In summary, $P1$ is the contribution of an entry point to the freeway congestion on a given segment, and $P2$ is a measure at which an entry point should be compensated for because its users do not contribute to congestion on a given freeway segment. Both $P1$ and $P2$ are calculated for each combination of $E(D)$ and $S(K)$ (i.e., the vehicles associated with entering the freeway at entry point E at time D, and that are present on segment S at time K).

3. The total metering-delay $M_{S(K)}$ is the summation of the delays across all entry points $E(K)$ triggered by congestion detected on $S(K)$. Time index K is used for both entry point and freeway segment. In most heuristic RM algorithms, the applied metering rate at $E(K)$ is set on the basis of the mainline traffic conditions measured at $S(K - 1)$; however, the sample control time-slices are significantly less than $T = 240$ s. With the selection of $T = 240$ s, the metering rates and slight fluctuations in traffic conditions are averaged out and the same K can be assumed for both detection and control.

On-ramp delays are measured in "on-ramp delay per vehicle" during one time-slice. The on-ramp delays are measured in 16-s intervals, and are aggregated to the 4-min time-slices using a weighted average derived from the count of vehicles exiting an on-ramp. If an on-ramp was switched off during a time-slice, the metering delay was assumed to be zero.

The metering delay, $M_{S(K)}$, requires an interpretation of the logic used in the RM algorithm to determine if the metering rate applied at $E(D)$ was caused by the congestion detected at $S(K)$. Table 2 shows how the HERO algorithm was been interpreted for this purpose. All possible causal conditions were considered by cross-referencing the

TABLE 2 Logic Used to Assign Segment as Trigger for Applied Metering to On-Ramp *I*

Coordination State of On-Ramp *I*	Modules of HERO Algorithm			
	ALINEA or ALINEA-PI	Queue Management	Queue Override	Minimum Queue
No coordination	Critical station for on-ramp *I*.	Critical station for on-ramp *I*.	Critical station for on-ramp *I*.	na
Master	Critical station for on-ramp *I*.	Critical station for on-ramp *I*.	Critical station for on-ramp *I*.	na
Slave	If on-ramp *I* would have been off without coordination, then use the critical station for the master on-ramp. If it was going to be on anyway, use critical station for on-ramp *I*.	If on-ramp *I* would have been off without coordination, then use the critical station for the master on-ramp. If it was going to be on anyway, use critical station for on-ramp *I*.	If on-ramp *I* would have been off without coordination, then use the critical station for the master on-ramp. If it was going to be on anyway, use critical station for on-ramp *I*.	Critical station for master on-ramp.

NOTE: PI = proportional integral; na = not applicable.

competing modules in the HERO algorithm with coordination states. Thus, by recording the coordination state and the winning module for determining the metering rate assigned at $E(D)$, the responsible $S(D)$ can be determined [see Papamichail and Papageorgiou (*31*) and Amini et al. (*32*) for an explanation of the HERO modules]. The HERO application programming interface (API) was modified to directly record the $S(D)$ responsible for the metering rate applied at $E(D)$ (Table 2) [Amini et al. (*32*) for the implementation of the HERO API].

The reallocation of the metering-delay at $E(D)$, according to the *IHE* definition, can be calculated as follows:

$$\sum_S \sum_K \left(P1_{E(D),S(K)} \times P2_{E(D),S(K)} \times M_{S(K)}\right) \tag{3}$$

The multiplication of the two proportions results in a loss of $M_{S(K)}$ because $\sum_E \sum_D (P1_{E(D),S(K)} \times P2_{E(D),S(K)}) \leq 1$. This issue is more prevalent in the PHE case, as $P1_{E(D),S(K)} = 0$ for entry points that are not controlled. The following formula can be used to ensure all of $M_{S(K)}$ is assigned to all contributing entry points:

$$d(E, D, S, K) = \frac{P1_{E(D),S(K)} \times P2_{E(D),S(K)}}{\sum_E \sum_D \left(P1_{E(D),S(K)} \times P2_{E(D),S(K)}\right)} \times M_{S(K)} \tag{4}$$

where $d(E, D, S, K)$ is the equitable delay that should had been experienced by $E(D)$ because of its contribution to $M_{S(K)}$. The final equitable delay $d(E, D)$ that should have been experienced at $E(D)$ is simply the sum of all the equitable delays across all $S(K)$s:

$$d(E, D) = \sum_S \sum_K \left(\frac{P1_{E(D),S(K)} \times P2_{E(D),S(K)}}{\sum_E \sum_D \left(P1_{E(D),S(K)} \times P2_{E(D),S(K)}\right)} \times M_{S(K)} \right) \tag{5}$$

The proposed solution is best described using the following example (Figure 1). Assume that the segment S^*, immediately downstream of On-Ramp 11, contains a bottleneck that results in some metering at time K^* (and thus a delay, $M_{S^*(K^*)}$) at On-Ramp 11. Given that some of the traffic from On-Ramp 12 ($E = 12$) contributes to this bottleneck (light blue route), On-Ramp 12 should be "punished" accordingly by being assigned some of the delay from On-Ramp 11. The equitable amount of delay to be applied at entry-time D^* [because of its contribution to $S^*(K^*)$] can be calculated using $P1_{12(D^*),S^*(K^*)} \times M_{S^*(K^*)}$. However, On-Ramp 12 should be "compensated" for the proportion of the traffic from On-Ramp 12 that never reaches the bottleneck (i.e., the dark blue route). The compensated amount of delay can be calculated by multiplying $(P1_{12(D^*),S^*(K^*)} \times M_{S^*(K^*)})$ with $P2_{12(D^*),S^*(K^*)}$. As noted, the inclusion of $P2$ in Equation 3 will result in some portion of $M_{S^*(K^*)}$ being assigned across all $E(D)$s. Equation 4 is used to assign equitably 100% of the experienced delay $M_{S^*(K^*)}$. After the equitable delays for all $M_{S(K)}$ on the freeway are calculated, Equation 5 is used to calculate the final equitable delay that should have been experienced at On-Ramp 11 during D^*.

Summarizing Equity Measures

The TDE is normally summarized with the following definition of the Gini coefficient:

$$G = \frac{1}{2\mu n^2} \sum_{i=1}^{n} \sum_{j=1}^{n} \left| x_i - x_j \right| \tag{6}$$

where

$$\mu = \frac{\sum_{i=1}^{n} x_i}{n}$$

and

x_i = average delay for ith on-ramp during study period,
n = total number of on-ramps in the study, and
μ = average metering delay across all on-ramps.

Thus, the most equitable condition using TDE is when $G = 0$, which is achieved by assigning the same delay across all on-ramps.

The proposed methodology for calculating IHE provides an equitable allocation of delays across every entry point and time. To summarize the IHE across all on-ramps and time-slices, first the difference between the IHE and the simulated delays for every entry point and time-slice, $E(D)$, is calculated. Thus, a perfectly equitable RM system would result in zero difference for every entry point and time-slice. The larger the differences, the more inequitable the system is, according to the definition of the IHE. However, given that the average of these differences is zero (as the sum of the total delays is the same), the Gini coefficient as defined in Equation 6 cannot be used; a normalized Gini coefficient is used instead. The normalized Gini coefficient was formulated by Raffinetti et al. and is defined when the attribute average is zero or negative (*33*). It defines the most inequitable condition as when one individual is assigned all the costs (i.e., negative values) and another individual is assigned all the benefits (i.e., positive values):

$$G_{\text{norm}} = \frac{1}{2(n-1)\sum_{j=1}^{n} |x_i|} \sum_{i=1}^{n} \sum_{j=1}^{n} \left| x_i - x_j \right| \tag{7}$$

where x_i is the difference between the measured delay at $E(D)$ and the final equitable delay $d(E, D)$ as per Equation 5. The summation is applied across all $E(D)$s.

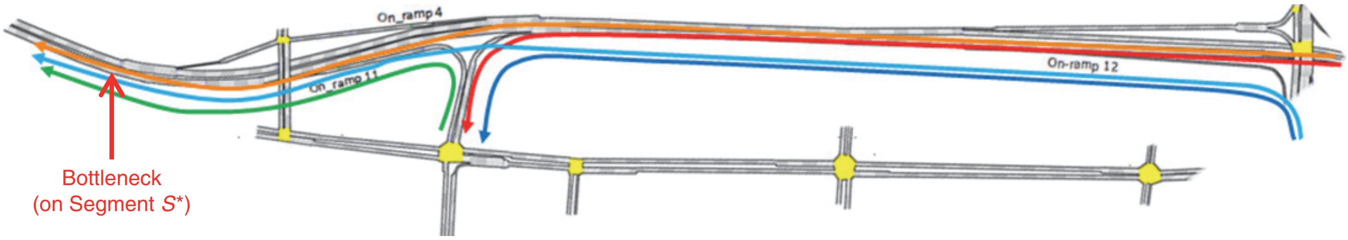


FIGURE 1 Contribution calculations.

CASE STUDY: APPLICATION TO A SYDNEY MOTORWAY

This section describes the application of a hypothetical microsimulation model used as the platform to implement and interpret the equity definitions. The network geometry has been drawn from a selection of Sydney's road network to ensure that the underlying infrastructure represents a realistic setting. The model includes a 25-km-long stretch of motorway with 17 on-ramps and 15 off-ramps [Figure 2(*a*)]. The parallel arterial roads were included to allow for diversions.

The details of the modeling approach and the implementation of the HERO algorithm using the AIMSUN API are described in Amini et al. (*32*). A heavily congested demand condition [referred to as the 1.5 Peaky demand condition in Amini et al. (*32*)] was applied, as a majority of the calibration was conducted for this scenario. To allow for comparison and interpretation of the proposed equity measure, two configurations of the HERO algorithm were simulated as shown in Figures 2(*b*) and 2(*c*). Scenario 1 allows for fewer on-ramps to be coordinated, as compared with Scenario 2. RM delays resulting from these simulations are referred to in the results as Simulation Scenario 1 and Simulation Scenario 2 and are reallocated using IHE and PHE equity definitions for comparison.

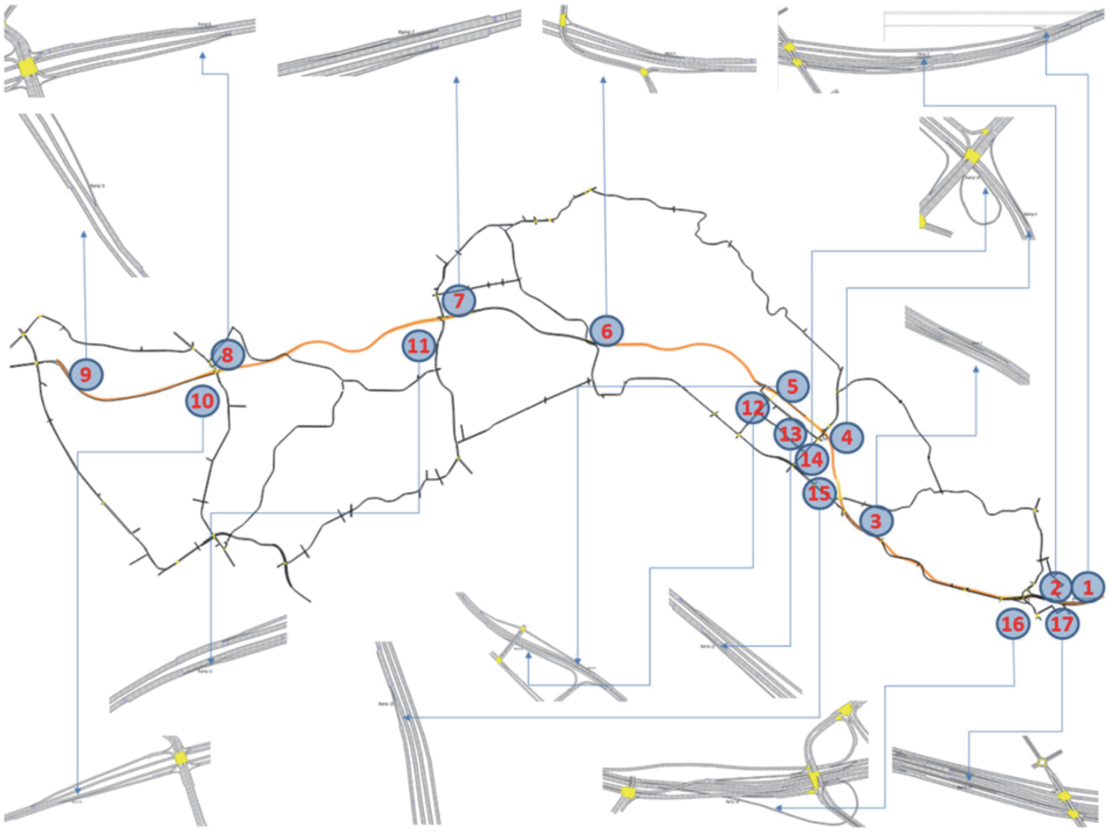
Obtaining On-Ramp Delays

The on-ramp delays were aggregated to the 4-min time-slices using the following methodology. If the occupancy of the 4.5-m-long queue detector (Figure 3) was less than 80%, the on-ramp delay from the internal subpath was used (recorded every 16 s). Otherwise, the queue was considered to have spilled back onto the arterial road network and the weighted delay (on the basis of traffic counts from each subpath) from the extended subpaths was recorded.

Evaluation Results

To interpret the results, the contribution of each entry point to each freeway segment should be considered. Scenarios 1 and 2 have a similar contribution from each entry point (Figure 4). Notable findings are that the majority of eastbound traffic enters the freeway from the upstream entry points, comprising mainline On-Ramp 9 and On-Ramp 8. In the westbound direction, the contribution is relatively more distributed across the entry points, with the exception of On-Ramp 11, which has a significant contribution immediately downstream (i.e., Segment 29). If a vehicle was present within a segment for *n* time-slices because of slow-moving traffic, it was counted as contributing to the congestion of that segment *n* times.

Table 3 shows the summary results of three equity definitions. The summary results for TDE cannot be directly compared with IHE and PHE, as the selected Gini coefficient formula and the measures used within the formula are different. However, the results indicate that Scenario 2 is slightly more equitable compared with Scenario 1 using TDE. This is contrary to the results obtained from IHE and PHE, which indicate that Scenario 1 is slightly more equitable than Scenario 2.



(a)

FIGURE 2 Microsimulation case study: (*a*) network geometry.

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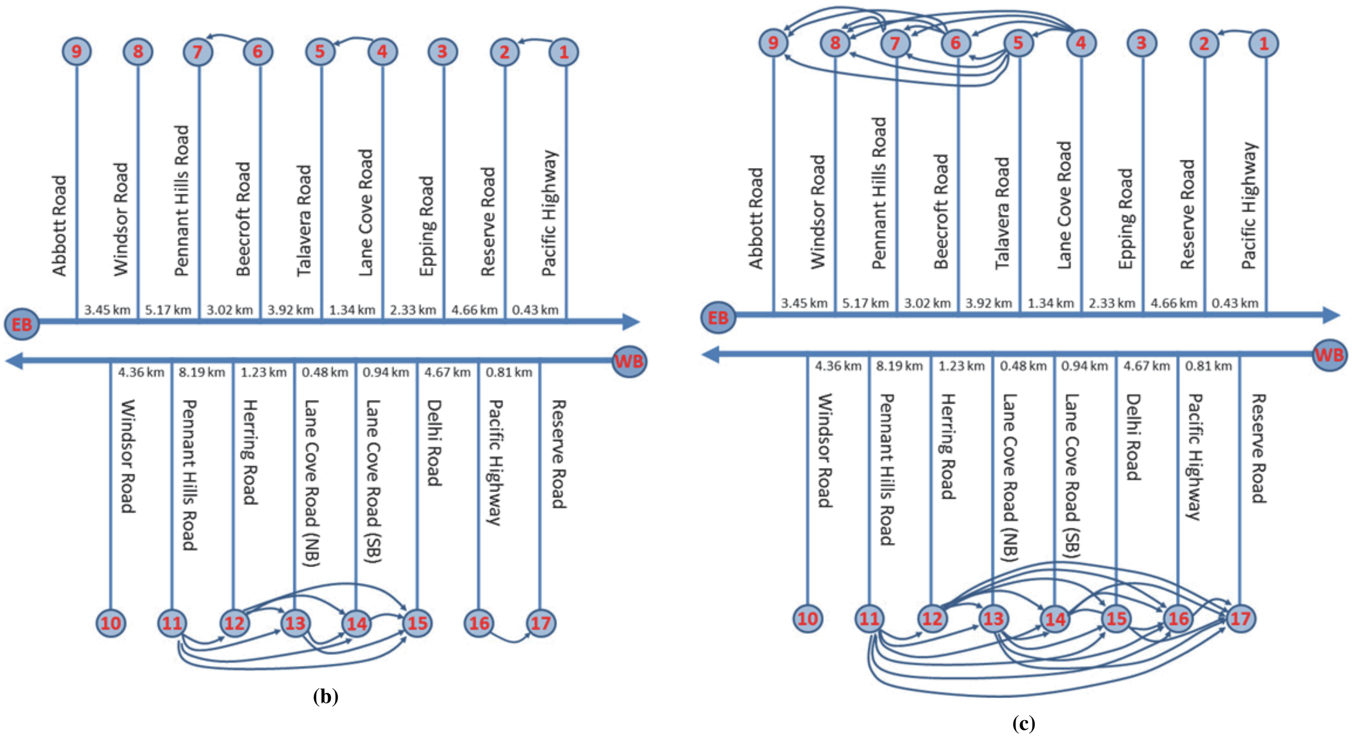
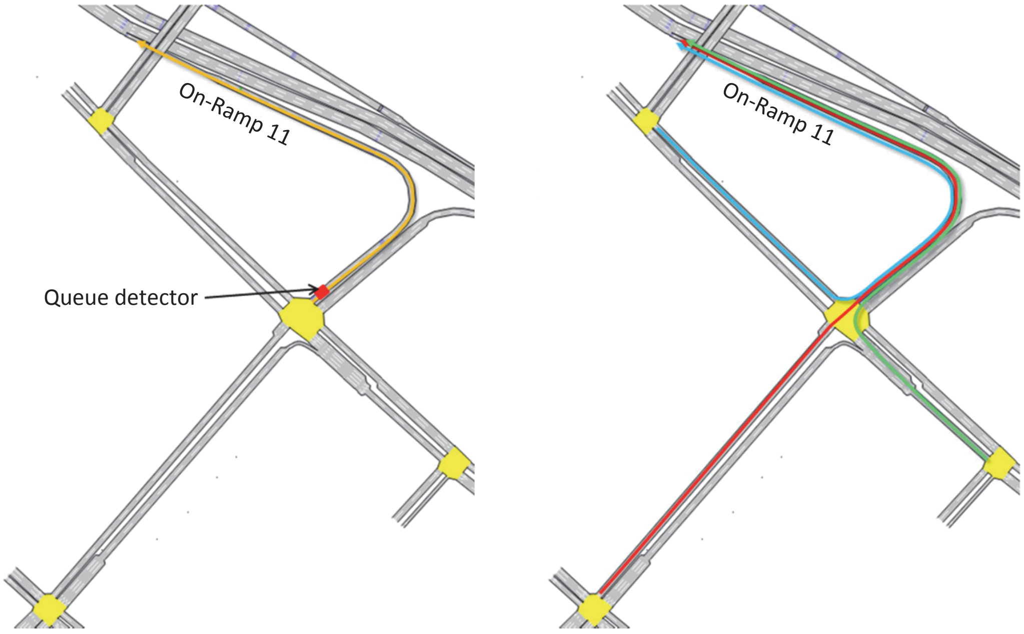


(b)

(c)

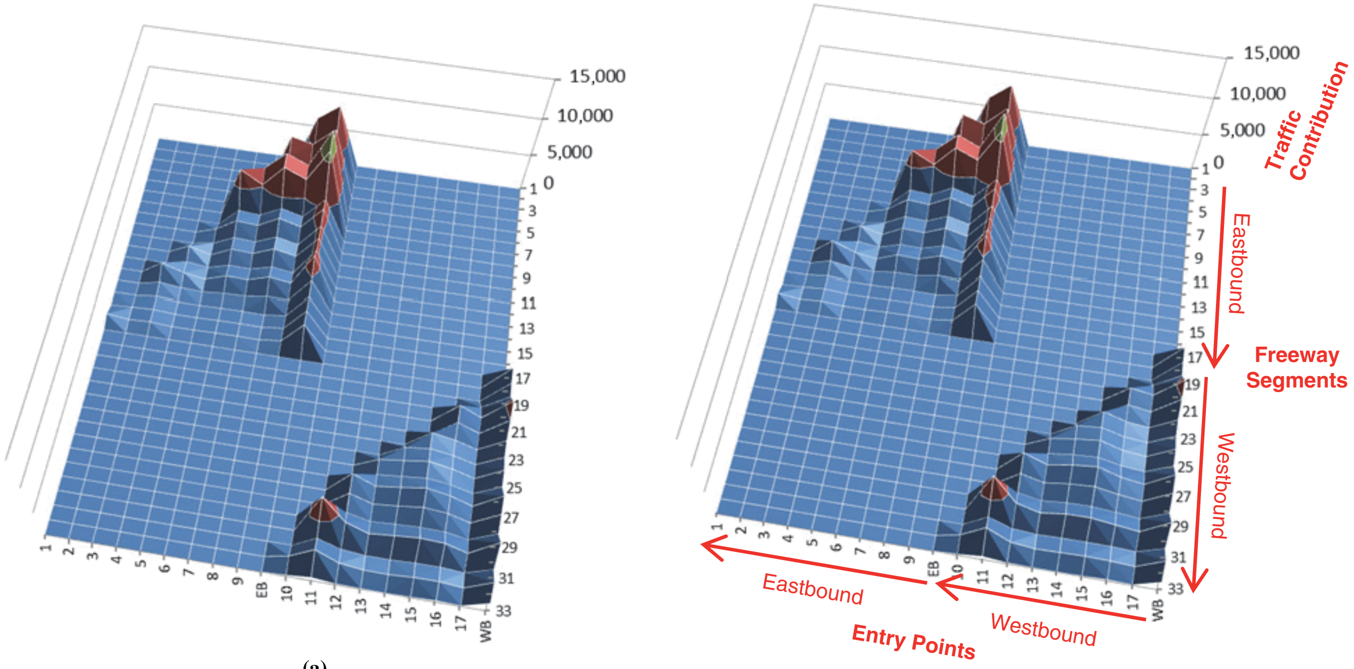
FIGURE 2 *(continued)* Microsimulation case study: (*b*) RM configurations for Scenario 1, less coordination; and (*c*) RM configurations for Scenario 2, more coordination.



(a)

(b)

FIGURE 3 Subpaths and queue detector used for measuring on-ramp delays: (*a*) internal subpath and (*b*) extended subpaths.



(a)

(b)

FIGURE 4 Contribution from entry points to freeway segments: (*a*) Scenario 1 and (*b*) Scenario 2.

Figures 5, 6, and 7 show the metering delays for the simulation, IHE, and PHE, respectively. These results are interpreted in the section that discusses the results.

DISCUSSION OF RESULTS

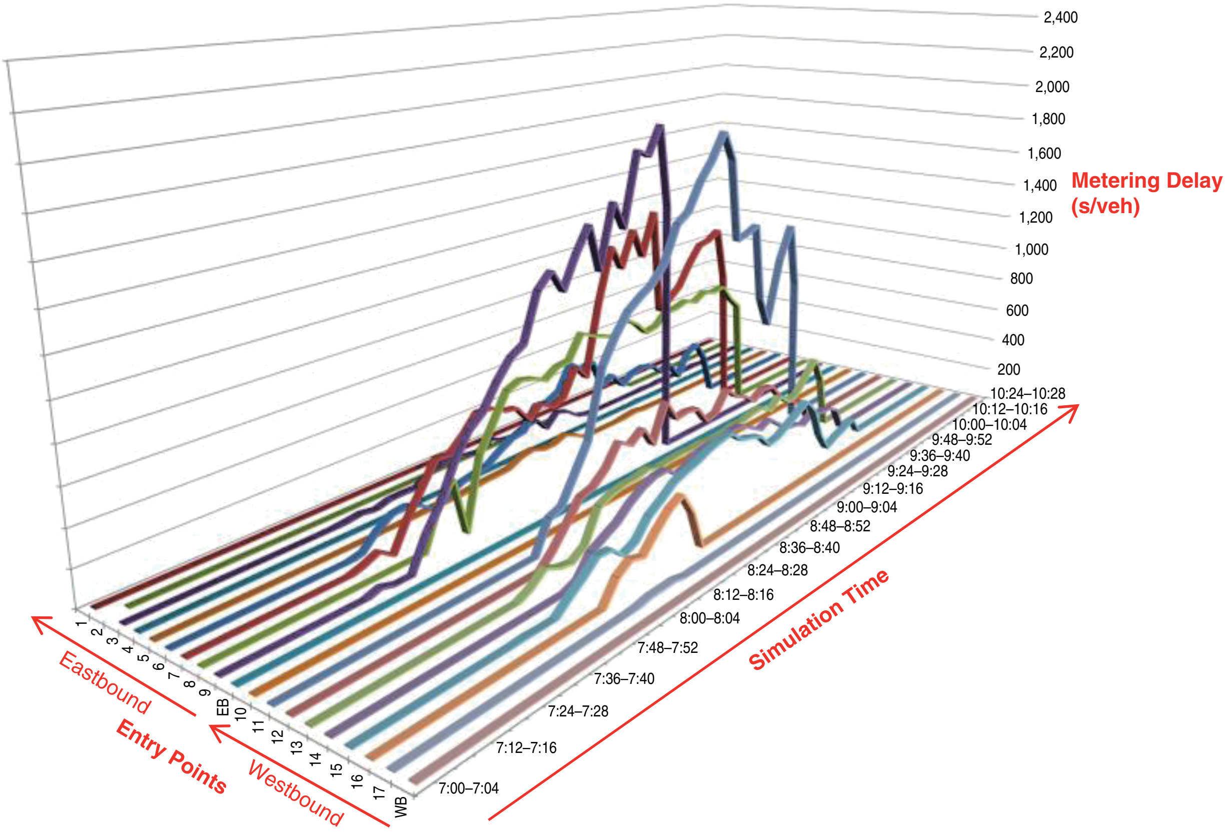
Figure 6(*a*) and 6(*b*) illustrate how the IHE has assigned a large portion of the metering delays to mainline entry points (i.e., eastbound and westbound). However, without freeway-to-freeway metering, the PHE is more useful. Figure 7(*a*) and 7(*b*) illustrate how the delay that was assigned to mainline entry points in the IHE has been equitably reassigned to the controlled on-ramps. The proposed methodology is flexible and can be used to reassign the metering delays equitably according to different criteria required by the system manager. IHE is useful to evaluate the equity of the overall freeway network, especially for long-term decisions such as deciding which entry points should be metered next. PHE was developed for incorporating back into the RM system, but it can also be used to compare different RM systems or to test different configuration settings given a set of controlled entry points. The results also indicate that the larger the number of uncontrolled entry points, the larger the inequity of the RM system.

The summary results (Table 3) indicate that TDE can favor scenarios that are different from those favored by IHE and PHE. The primary reason that IHE and PHE favor Scenario 1 is because of the logic used to assign on-ramp delays to a congested mainline segment (especially in relation to the extremely high demand at On-Ramp 9). TDE is fundamentally different from both IHE and PHE, as the latter are able to accept low metering delays if the on-ramp makes a small contribution to the mainline congestion. For example, Figures 7(*a*) and 7(*b*) show that On-Ramps 1, 2, and 10 are not assigned any metering delay by the PHE. In contrast, the TDE would indicate inequality in the absence of delay at any on-ramp.

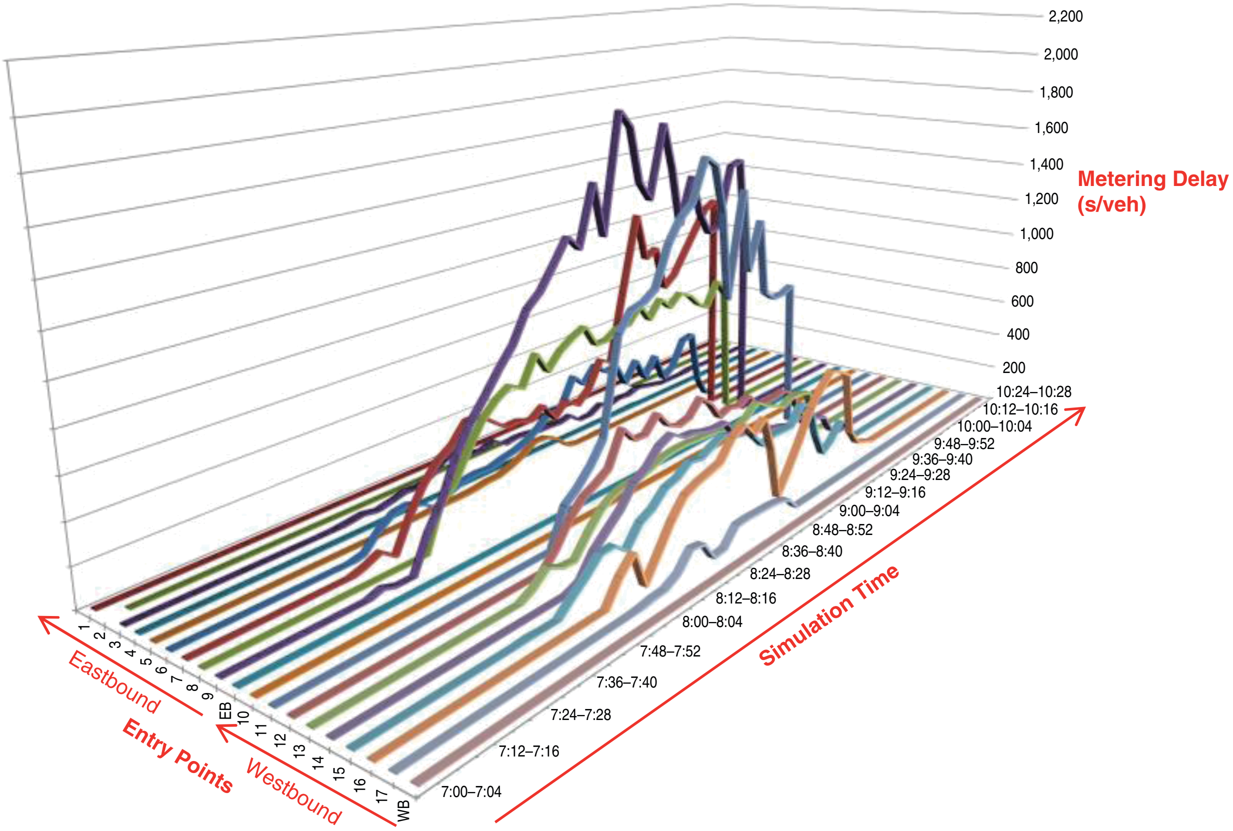
In both IHE and PHE results, one of the major differences between Scenario 1 (lightly coordinated) and Scenario 2 (highly coordinated) is the large delay assigned to On-Ramp 9 in Scenario 1 [Figure 7(*a*)], in contrast to Scenario 2 where a large delay is assigned to On-Ramp 6 [Figure 7(*b*)]. The reason for this difference is the logic that is used (Table 2) to associate the segment responsible for the metering delay. During the simulation, On-Ramp 9 experiences the largest delay compared with the other on-ramps in both scenarios [Figures 5(*a*) and 5(*b*)]. In Scenario 1, On-Ramp 9 is not coordinated with other on-ramps. Thus, any metering experienced by On-Ramp 9

TABLE 3 Summary Results of Equity Measures

	Equity Components			Summary Results	
Equity Type	Impact	Measurement	Formulation	Scenario 1	Scenario 2
TDE	Average metering delay during study period	Per on-ramp	G using Equation 6	0.5966	0.5755
IHE	IHE delay—simulated delay	Per entry point and entry time, $E(D)$	G_{norm} using Equation 7	0.9152	0.9159
PHE	PHE delay—simulated delay	Per entry point and entry time, $E(D)$	G_{norm} using Equation 7	0.9111	0.9345

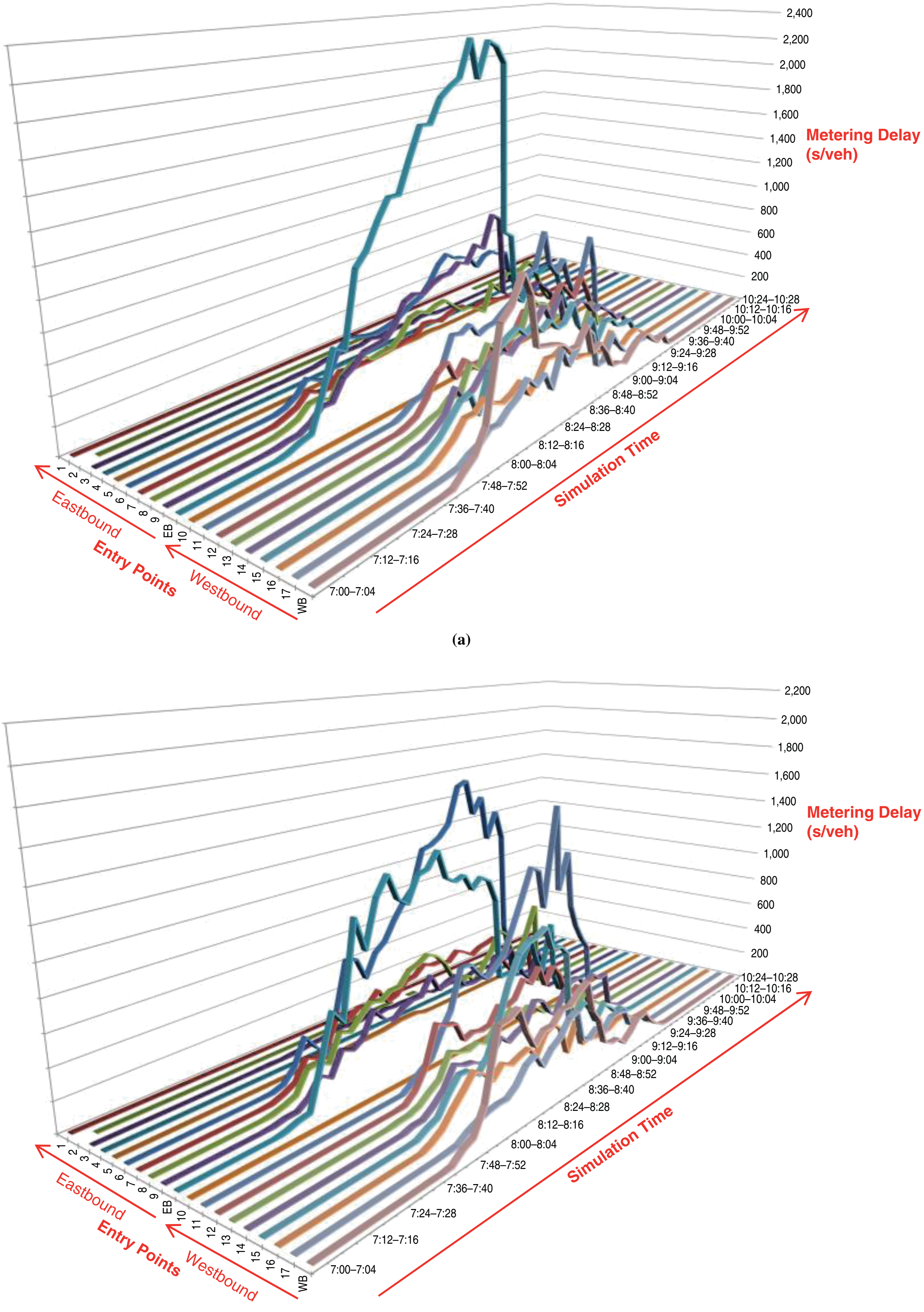


(a)



(b)

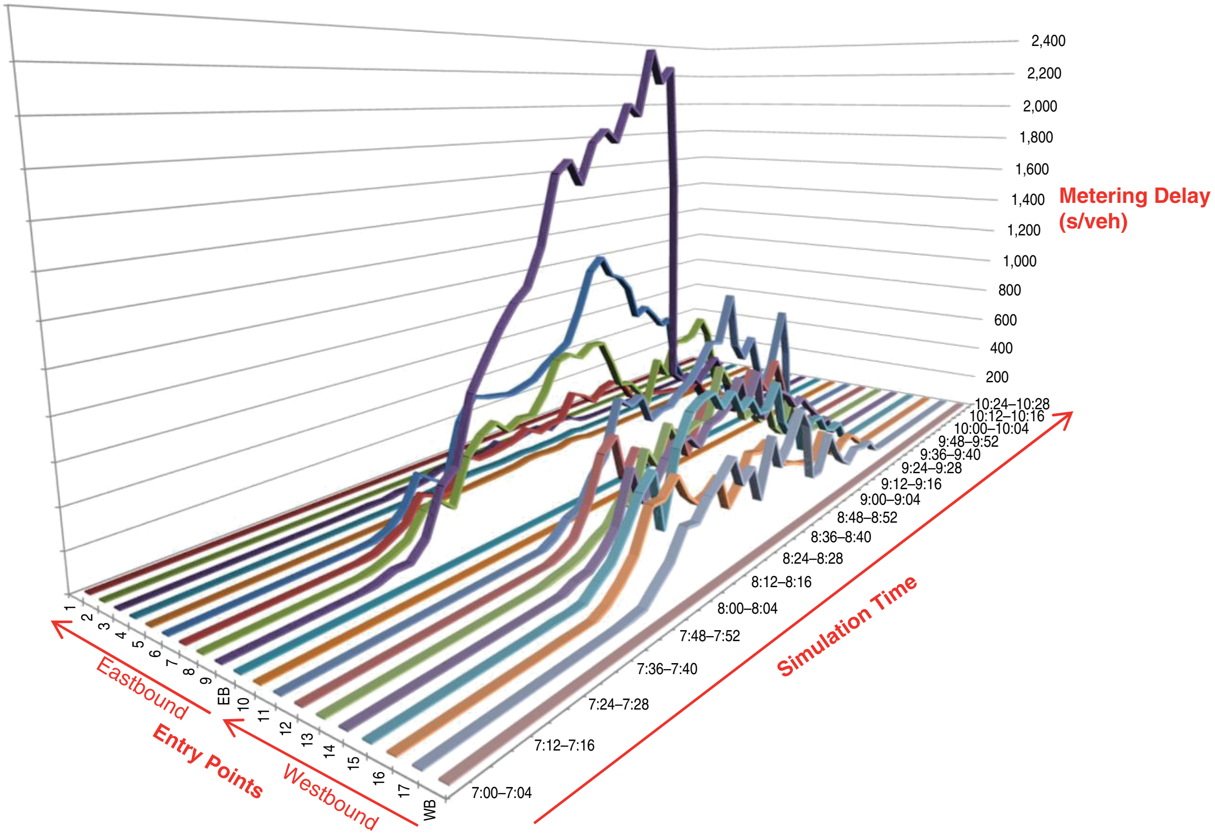
FIGURE 5 Metering delays observed from simulation: (*a*) Scenario 1 and (*b*) Scenario 2 (s/veh = seconds per vehicle).



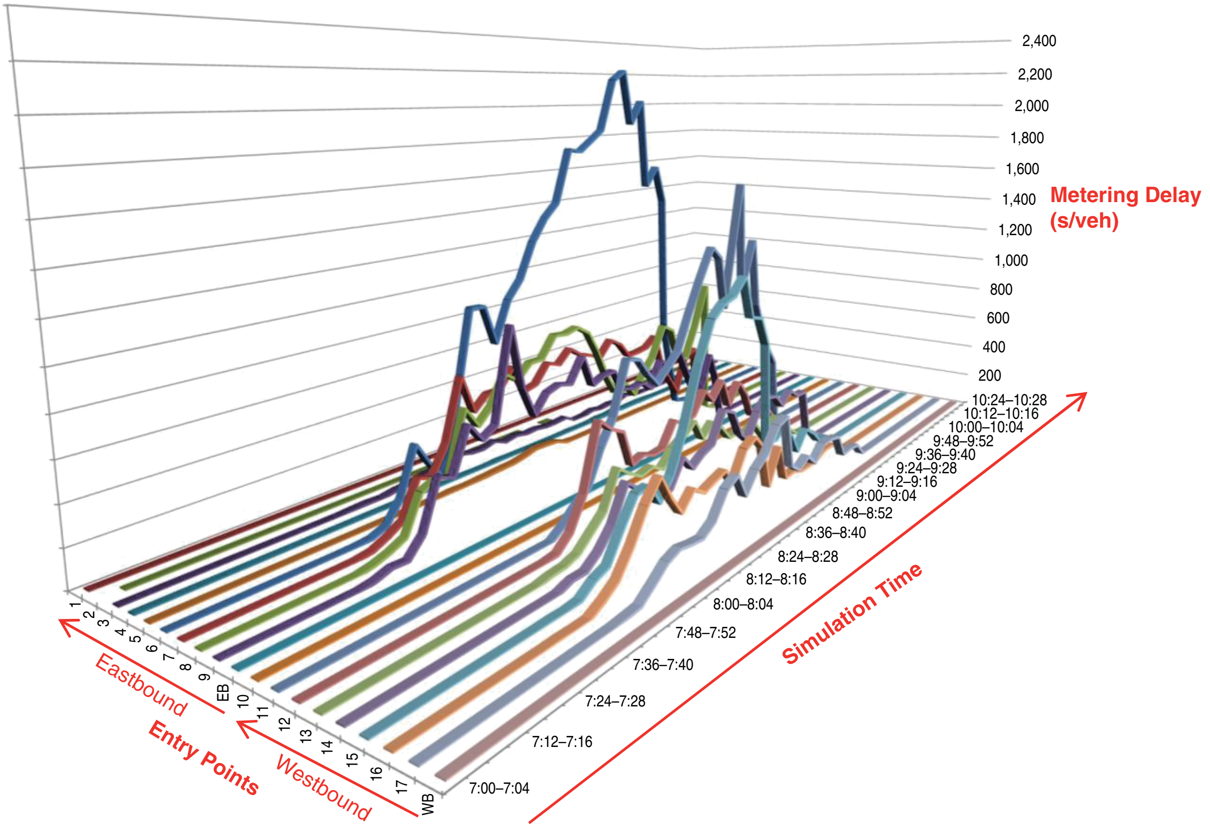
(a)

(b)

FIGURE 6 Reallocation of metering delays using IHE: (*a*) Scenario 1 and (*b*) Scenario 2.



(a)



(b)

FIGURE 7 Reallocation of metering delays using PHE: (*a*) Scenario 1 and (*b*) Scenario 2.

was associated with the bottleneck immediately downstream, even though it also contributed a significant amount to the highly congested bottleneck downstream of On-Ramp 6. Thus the equitable distribution assigned more delay to On-Ramp 9. In Scenario 2, On-Ramp 9 was coordinated with On-Ramp 6. As a result, the trigger of the delay at On-Ramp 9 was associated with the bottleneck segment downstream of On-Ramp 6. Given the relatively large delay at On-Ramp 9, and the fact that 100% of the traffic from On-Ramp 6 entered this bottleneck, the equitable distribution assigned most of the delay to On-Ramp 6. Although the large delay at On-Ramp 9 is because of its restricted geometry (i.e., a three- or four-lane entry is required for ramp metering to be able to adequately address the large demand at this on-ramp), the extreme example has been used to highlight how the logic of the RM algorithm is used in the proposed methodology.

A commonly encountered scenario is observed in the westbound direction, where the PHE for Scenarios 1 and 2 have resulted in a similar delay profile for On-Ramp 17 [Figure 7(*a*) and 7(*b*)]. This on-ramp is assigned more delay in the PHE compared with the simulation, for both scenarios. By the time the coordination from downstream on-ramps is activated (i.e., cluster formations), the traffic from upstream on-ramps has already entered the freeway without paying any metering delay, but causing delay for other motorists. Thus, it seems fair that On-Ramp 17 should experience some of the metering delay earlier in the simulation. The timing and amount of this anticipated delay is provided by the PHE.

On the basis of the results from this analysis, implementing the proposed equitable delays would result in more restrictive metering at upstream on-ramps when there is typically a large freeway capacity available. This condition was noted in the user surveys as a phenomenon that motorists do not accept easily, but may be willing to accept if the proposed equity measure were communicated to them (i.e., that they are the reason for their own delay). One advantage of the proposed equity measure is that conceptually it is intuitive and relatively simple to communicate. It also assigns the cause of the delay back to the user, which may be more acceptable to the public. A user survey would have to be conducted to evaluate whether the application of this equity measure would in fact increase public acceptance.

Another advantage of implementing the proposed equity measure is that it can be aligned with the long-term traffic demand management goals of the road authorities. This is because regular users of RMs are well tuned to the changes to on-ramp delays (*15*); thus, it is expected that implementing the anticipated delays may result in changes to long-term travel patterns, especially for the motorists with longer trips. These changes may occur in the form of departure times, diversions, or the choice of entry point location, destination, or mode, all of which would reduce the number of vehicles on the freeway (during congested periods) in the long term. A stated preference survey has shown that 70% to 75% of motorists traveling through ramp meters sometimes modify their departure time choice of entry point, or re-route to avoid congestion and on-ramp delays (*15*). However, these responses were focused on the short term; long-term traffic patterns may change in relation to car ownership, mode choice, and even residential location (*34*).

Finally, the proposed RM equity measure is expected to be complementary with tolling, where bypass lanes allow users to pay instead of waiting at the metered on-ramp. The bypass lanes could also reduce the burden on the shorter trips that do not contribute to freeway congestion, thus allowing an even more efficient and equitable RM system.

One of the assumptions of the proposed equity measure is that all vehicle trajectories can be obtained. Although this is unrealistic at the present time, origin–destination estimation on freeways is currently done using WiFi, Bluetooth, and tolling system technology (*35, 36*). Data sets of this type are currently in development; it is reasonable to expect that the measured vehicle trajectories will become more accurate as tracking technology matures. Future research will address the impact of real-life limitations, such as having access only to a limited sample of vehicles with vehicle identification devices.

Another issue that has to be resolved before implementing the proposed equity measure is that the proposed methodology requires foresight—that is, the proposed equity measure can be calculated after vehicles complete their trips. Two possible solutions are (*a*) to use the calculated equitable delays from previous days, assuming that similar traffic patterns will be repeated, or (*b*) to use real-time data to estimate the "near future" time-dependent origin–destination matrix with machine learning techniques. Then calculate the equitable delays can be calculated using a model predictive control scheme (*37*). Regardless of the method that is selected to estimate the equitable delays, the resulting equitable delays should be applied conservatively (i.e., less restrictive metering rate). The level of conservatism should be determined by the amount of expected error associated with the selected method. This is to ensure that unnecessary delays would not be experienced by users who would then reject the system. The exact details of these will be explored in future research.

CONCLUDING REMARKS

The literature review revealed that RM equity has been evaluated and incorporated with the purpose of avoiding user rejection of the RM system. The typical definition of equity evaluated relied on the equality of metering delays across the metered entry points. A detailed review of user surveys indicated that the reasons for resisting RMs included the unfair distribution of benefits to drivers who enter the freeway upstream at the expense of the drivers who enter further downstream. Other objections are connected to the level of user knowledge and confidence in the RM system.

An intuitive and horizontal definition of equity was proposed, with the aim of assigning a freeway entrance delay on the basis of the amount of congestion a motorist will cause on the freeway. A methodology for evaluating the proposed equity definition was proposed and evaluated for a hypothetical microsimulation model, using two configurations of a ramp metering algorithm to aid in interpretation of the results. The proposed equity measures were compared with the typical equality measure used to evaluate RMs and the proposed equity measures were shown to be more flexible. The results showed that these measures can favor different scenarios compared with the typical equality measure. In addition, the following factors were considered in the proposed equity measure: dynamic demand for each on-ramp (i.e., the changes to the congestion contributions from an on-ramp over time); the travel time required to reach a bottleneck (particularly for bottlenecks located at long distances from the on-ramp); the amount of time spent in a bottleneck (i.e., the duration for which a vehicle is contributing to a congested bottleneck); and the consideration of on-ramp delay for motorists not contributing to the congested bottleneck or bottlenecks. The proposed methodology can be built on top of most heuristic RM algorithms; thus, it builds on the existing body of knowledge and is complementary with most RM systems that are in operation.

Application of the proposed equity measure is expected to increase user acceptance and can assist road authorities with long-term demand management (by ensuring that suburban motorists are also assigned an equitable on-ramp delay). Future research will focus on application methodologies, such as using historical equitable delays, or calculating real-time equitable delays using the model predictive control scheme. The effects of applying the proposed equity measure with real-world limitations will also have to be tested. Surveys of users' acceptance of the proposed equity measure should also be conducted.

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