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Modeling Highway Congestion Index for a Developing Country: The Iran Experience

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This paper describes an attempt to develop congestion indices for a developing country with a limited sampling. Speed and flow rate information was collected from urban highway traffic flow videotaping in Iran. Video display provided information for traffic modeling when, similar to most of the developing nations, Iran does not have locally developed highway capacity manuals. Processing of the extracted data and traffic modeling provided free and capacity flow information for the selected freeway and principal arterial sections for the capital city of Tehran. The congestion indices were associated, in simple and logical models, with five traffic descriptive variables of travel speed, travel rate, delay rate, travel rate ratio and delay ratio, respectively. To calibrate the congestion index models, specific congestion levels were assessed by the index values under free and capacity flow conditions. The functional forms used in congestion index modeling were derived from the congestion rate of change, simple, reasonable and relevant assumptions. For comparison, index models, based on the US Highway Capacity Manual, HCM, speed and flow rate information, were also developed. The developed indices were suggested as feasible and included quick response measures for congestion monitoring and control when traffic management resources are often limited and scarce. Based on the preferences of a group of transportation professionals and university students, the relative importance of each of the individual indices, as average weighting value, was identified. Using the average weighting values, an overall congestion index was also developed. The overall congestion index was suggested as a complimentary or alternative measure for congestion intensity assessment and evaluation. The study findings were based on a rather limited database and were location specific; nevertheless, for quick response congestion index development, the applied methodology could be used by any developing country. The suggested indices have potential in traffic management and congestion mitigation.

INTRODUCTION

Large cities in developing countries, especially in the Asia-Pacific region, are characterized by a continuing growth in automobile ownership and by insufficient transportation infrastructure and service development. These cities most often suffer from chronic highway congestion, echoed by poor mobility and accessibility, significant economic waste, adverse environmental impact and safety problems. Their transportation professionals are facing a tremendous challenge in treating traffic congestion. With limited resources and technology, to mitigate congestion, traffic components should be continuously coordinated. This should occur when achieving sustainable harmony among users, vehicles, control systems, highways and the environment, is perceived at its most challenging.

Assessing the state of highway traffic and service conditions is an essential task for developing countries' transportation professionals. Congestion is one of the key operational attributes to assess and evaluate overall highway performance. It reflects slowness and immobility, due to traffic crowding and accumulation. The definition and quantification of congestion have been related to its causes and effects. Congestion occurs when traffic demand approaches and exceeds highway capacity. Increase in travel time and delay are the main congestion effects. To characterize congestion, the selection of measures, indicators and indices should be relevant to the study purpose and scope. Most

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traffic congestion studies are reported for developed countries [1-7]. Research for developing nations is deemed crucial for improved resource allocation in infrastructure and service development. The reported congestion studies vary from addressing transportation unimodal issues at a local level up to solving multimodal problems on a regional scale.

Characterization of traffic congestion should address its three major aspects namely; intensity, extent and duration. Congestion intensity has also been defined as congestion severity or magnitude. Several studies have tried to develop a comprehensive congestion index, when the index promises to show all congestion intensity, extent and duration characteristics in a single measure. If the congestion intensity for a roadway in time and space is determined, it can be aggregated, integrated, normalized or weighted over time and space to also reflect congestion extent and duration. In past studies, congestion intensity had been considered either on discrete or continuous scales. In Iran, local transportation officials have often used the 1985 HCM concept of level of service A to F as also covering and reflecting the levels of congestion intensity [8]. The lane kilometer duration index, which considers the level of service F to define the threshold for congestion, has also been used. This index reflects the extent and duration of recurring highway congestion in lane kilometer hours [2]. In developed countries, urban traffic detector networks, enhanced and augmented with advanced information and computational technologies, often provide real time freeway queue and lane occupancy rates. This information is often associated with and translated to congestion intensity levels in nominal or ordinal scales, to provide pertaining congestion level minute kilometers. However, this method is not usually feasible in developing nations, due to technological and financial constraints. The delay rate index, DRI, is an index that associates congestion intensity to the differences in actual versus desired travel times. The DRI provides a continuous scale in the range of 0 to 10 [4,5]. Local transportation officials in Iran have recently advocated similar indices that directly address congestion, instead of HCM levels of service that reflect overall highway quality of service.

In the reported studies for developed nations, traffic flow and congestion travel time-based characteristics have been used as descriptive variables or indicators of congestion intensity. The descriptive variables have sometimes been used directly to represent, or as substitutes for, congestion intensity. Travel delay, measured in minutes per trip or minutes per vehicle kilometer, has been used for congestion intensity presentation. Travel speed, travel rate or slowness, delay rate, travel rate ratio and delay ratio are among key congestion descriptive variables used in past studies [1-7]. The relationships between these descriptive variables are shown in the following equations:

$$\mathrm{TRA} = 60/\mathrm{TSP}. \tag{1}$$

The travel rate, TRA, in minutes per kilometer, is the inverse of travel speed, TSP, in kilometers per hour, multiplied by its relevant conversion factor.

$$\mathrm{DRA} = \mathrm{TRA} \quad \mathrm{TRD}. \tag{2}$$

The DRA is the difference between the travel rate in the prevailing condition, TRA, and the travel rate in the desirable travel condition, TRD, and is in minutes. Travel rate during the HCM level of service A, free flow or off-peak period, is often assumed by researchers and transportation professionals to reflect desirable travel conditions [8-10].

$$\mathrm{TRR} = \mathrm{TRA}/\mathrm{TRD}. \tag{3}$$

The TRR is dimensionless and is the ratio between the travel rate in the prevailing condition, TRA, and the travel rate in the desirable travel condition, TRD.

$$\mathrm{DLR} = \mathrm{DRA}/\mathrm{TRA}. \tag{4}$$

The DLR is dimensionless and is the ratio between the prevailing delay rate, DRA, and the prevailing travel rate, TRA.

Since a scale of values for expressing congestion intensity is a much more elusive measure, it is often expressed by an index [1-7]. Reference points or bases are needed if the congestion intensity index is to be defined in a discrete or continuous scale. The overall operational condition of level of service D, or worse, is often assumed to be coexisting with highway congestion, such as for the lane kilometer duration index for level of service F. This could be considered as at least identifying intensity in a nominal scale for congestion existence, measured by a value of either zero or one. The congestion intensity could be defined in an ordinal scale, such as in three levels, being associated with the levels of service of D, E and F, respectively. The reference point for congestion intensity in a continuous scale is often determined by desirable travel conditions, such as in the aforesaid delay rate index, DRI [4,5]. Operational conditions of level of service A, free flow or off-peak periods, are assumed to reflect desirable travel conditions. The unacceptable congestion level reflects congestion intensity in excess of an agreed-upon norm. The threshold defining unacceptable congestion varies by geographic location, time period, mode and facility type, reflecting the different perceptions, expectations and objectives of trip makers. Fuzzy set theory and inference have also been used in developing continuous congestion indices within ranges of zero to one [3,7].

Once a congestion intensity measure is selected or developed, it will be then aggregated, integrated, normalized or weighted over time and space to also reflect the congestion scope and duration. The average congestion intensity is utilized to present the average over a specific time period for a given geographical area. The geographical area can have a wide range, from a short roadway section to a large geographical region, such as a city, determined by the study scope. The time period can be any period from a second to a year, determined, also, by study scope. The number of persons, vehicles, or trips affected by congestion can also be used to reflect the congestion extent and duration.

This paper presents a study in developing freeway and arterial congestion indices, based on videotape-observed data at a limited number of sites. The objective of the study was to develop congestion indices to quantify and assess the congestion intensity on Iranian highways with limited traffic sampling and the nonexistence of a local highway capacity manual. It demonstrates an example of congestion index modeling for a developing country. Among several possible congestion intensity indices, associated with travel speed and time, five types were selected for detailed evaluation. These indices were assumed dependent on descriptive variables of travel speed, travel rate, delay rate, travel rate ratio and delay ratio, respectively. Individual developed indices were suggested as congestion measures. Combining the developed indices, based on the weightings of an opinion survey, an overall congestion index was also suggested. Although the study findings are based on a rather limited database and are location specific, the same methodology could be applied to any highway congestion assessment for developing nations that are short of locally developed capacity manuals.

CONCEPTUAL CONGESTION MODELING

Various descriptive variables were investigated for inclusion in congestion intensity index development. They include the HCM level of service measures of effectiveness, their surrogates and congestion travel time-based measures [8-10]. In this study, the above-mentioned five descriptive variables of travel speed, travel rate or slowness, delay rate, travel rate ratio and delay ratio, as described by Equations 1 to 4, were evaluated. The main reasons for their selection were:

- They were applicable in a wide range of congestion analyses;
- They have been used in past congestion studies;
- They could furnish discrete or continuous congestion index values;
- They were easily measured and/or estimated;
- They were understood by both transportation professionals and community groups;
- They reflected the congestion effects of increased travel time and delay.

For these five descriptive variables, the following equation is a general presentation of such a congestion intensity index development:

$$\text{CII} = f(\text{TSP, TRA, DRA, TRR, DLR}), \tag{5}$$

where CII is the congestion intensity index, f represents the functional form, TSP is the travel speed in kilometers per hour, TRA is the travel rate in minutes per kilometer, DRA is the delay rate in minutes per kilometer, TRR is the travel rate ratio and is dimensionless, and DLR is the delay ratio and is dimensionless. Without any prior knowledge about the functional form of Equation 5, assumptions about the rate of change of congestion intensity, with respect to the descriptive variables, were made. To develop a congestion intensity index by simple and comprehensible forms, a single variable was used in each model, as in the past studies [4,5]. Furthermore, Equations 1 to 4 show linear and/or non-linear relations between the above mentioned five descriptive variables and, accordingly, discourage their simultaneous consideration in multivariable models. Consequently, the congestion intensity index models developed in this study were univariable models. The exception was only the development of a multivariable model to reflect an opinion survey, later explained by Equation 17. A general relation, such as Equation 6, can present the rate of change of congestion intensity index, CII_x, as a function of a single descriptive variable, X:

$$d\text{CII}_x/dX = g(X), \tag{6}$$

where $d\text{CII}_x/dX$ is the rate of change of congestion intensity index, CII_x, with respect to the descriptive variable, X, g presents the functional form and X can be any descriptive variable judged relevant to explain congestion. Equations 7 to 9 present the three types of rate of change that were found to be logical and simple to use in this study. Equations 7 and 8 present the rates of change previously assumed by Levinson and Lomax in developing the delay rate index, DRI [4,5]. Also, Equation 7 presents a uniform rate of change and Equation 8 presents a non-uniform rate of change, inversely proportional to X. Equation 9 presents a non-uniform rate of change, linearly proportional to X. These are the simple and logical forms, which guarantee that the rate of change of congestion intensity does not change the sign for any real value of descriptive variables, as well as conforming to functional forms used by other researchers [4,5,7].

$$d\mathrm{CII}_x/dX = k_1, \tag{7}$$

$$d\mathrm{CII}_x/dX = k_2/X, \tag{8}$$

$$d\mathrm{CII}_x/dX = k_3 X, \tag{9}$$

where k_1 is a constant and k_2 and k_3 are coefficients. Equations 7 to 9 result in linear, logarithmic and quadratic relations of Equations 10 to 12, respectively.

$$\mathrm{CII}_x = k_{01} + k_1 X, \tag{10}$$

$$\mathrm{CII}_x = k_{02} + k_2 \ln X, \tag{11}$$

$$\mathrm{CII}_x = k_{03} + 0.5 k_3 X^2, \tag{12}$$

where k_{01}, k_{02} and k_{03} are constants. These forms were favored because of their simplicity, comprehensibility and usage in past studies. Equations 7 to 9 present the study of selected single-regime rates of change. Evaluation of other single regime forms, such as any combination of the aforesaid forms or multiple-regime rate of change forms, could have enhanced the study results; nevertheless, the limited study resources confined the scope of the study to the single-regime rate of change.

Once a congestion intensity index model, such as Equations 10 to 12, is calibrated and selected, it can be used to compute index values. The computed values can then be aggregated, integrated, normalized or weighted over time and space to also reflect the congestion extent and duration. The average congestion intensity can be presented by the average of CII_x for a study area, whether that is a short roadway section, a corridor or a region. The amount of time that the system is congested can be illustrated by calculating weighted CII_x values over the study period. The number of persons, vehicles, or trips affected by congestion, as indicated by the CII_x, can also be illustrated by weighted averages.

To calibrate congestion index models, congestion levels are often associated with descriptive variables at key traffic operational conditions. Past studies have selected key traffic operational conditions at different levels of service, under free and capacity flow conditions. Due to the lack of any relevant local highway capacity information for Iran, to determine key traffic operational conditions, speed and flow rate information was extracted from traffic flow sampling and video display for a quick response assessment [11]. Processing of the collected data and traffic modeling provided the values of selected descriptive variables under free and capacity flow conditions. Similar to past studies, a single descriptive variable was used in each congestion index model. This resulted in simple and more comprehensible relations, as well as avoiding the appearance of correlated exogenous variables. To reflect congestion intensity on a continuous scale, a proper range from 0 to 10, similar to past studies, was selected [4,5]. Similar to past studies, the free flow condition, presenting desirable travel condition, was assumed to present zero congestion intensity or congestion free. Furthermore, similar to past studies, the mid range congestion intensity point, 5, was associated with the capacity flow condition. The study index model development consisted of data collection, analysis and calibration, respectively.

TRAFFIC DATA COLLECTION

Discussions with local traffic engineers led to the identification of 4 freeway and 4 principal arterial candidate sites in the metropolitan area of Tehran. Of these sites, 2 freeway and 2 principal arterial sections that showed more traffic variations were selected for final data collection. Using more than 4 sites could have enhanced the study results, but, the limited study resources confined the scope of the study to the selected sites. Using a video camera with a timer, the traffic behavior was taped. The selected freeway sites were six-lane and eight-lane sections, with ideal geometric designs and no adjacent ramp or weaving sections, respectively. The selected principal arterial sites were two six-lane arterials with a 3.3 meter lane width, conforming to local ideal design standards. The video cameras were located on pedestrian over-passes, to clearly capture traffic behavior from up to 200 meters away. At each site, 4.5 hours of videotapes were recorded from 7:00 a.m. to 9:30 a.m. and 3:30 p.m. to 5:30 p.m. on a Wednesday of October 1998. Longer videotaping could have improved the study results; but, the limited study resources confined the videotaping to a total of 18 hours. During the videotaping, no unusual event or traffic accident occurred. Commercially available image processing hardware and software could have been used to determine traffic behavior, but, the limited study resources made it impossible to acquire such facilities [12]. A similar study in any developing country would most probably face the same reported types of financial and technological constraints.

The videotapes were reviewed and information about the traffic behavior was extracted from the display on the television screen. The flows and travel times for the 200-meter interval were measured by a hand traffic counter, the time recorder was dubbed to the tape using a hand chronometer with a tenth of a second precision. To compute space mean speed, for each 5-minute interval, vehicle travel times for the 200-meter interval were used. Density was then computed from the flow and speed information. The study database consisted of freeway and principal arterial 5-minute interval traffic characteristics for 216 samples. For each 5-minute interval, the database has information about the observed speed and flow and the estimated density. Due to the traffic ban on metropolitan area truck movements from 7:00 a.m. to 8:00 p.m., no truck traffic was observed in the videos. Buses constituted less than 1.5 percent of the traffic.

TRAFFIC DATA ANALYSIS

Traffic-flow theorists have studied various mathematical formulations that may be used to describe the relationships between flow, speed and density. The exact model that best describes these relationships may vary from location to location and may be determined by examining and trying several different forms. For the observed traffic speed and estimated density, six single-regime and three two-regime models were evaluated, using regression analysis for the 216 data points. The single-regime models consisted of Greenshields, Greenberg, Underwood, Drake, Pipes and Munjal and Drew models, respectively [11]. The simplest was Greenshields' assumption of a linear speed-density relationship. Greenberg used a logarithmic relationship. Underwood proposed a negative exponential form. Drake used a bell-shaped or normal curve. Pipes and Munjal and Drew proposed generalized single-regime models. The two-regime models consisted of different combinations of Greenshields and Greenberg models, respectively.

Using a root mean square of error as the evaluation criterion, the most superior, statistically significant models from all the calibrated models were determined. For the models whose estimated coefficients and constants were statistically significant at a level of 0.05, the least root mean square of errors for the freeway and principal arterial calibrated models were observed for the Greenshields and the two-regime Greenshields-Greenberg models, respectively. The selected freeway model with the observed least root mean square of error 2.453 was:

$$\mathrm{TSP} = 98.62 \quad 0.92\ \mathrm{DEN}, \tag{13}$$

where TSP is the speed in kilometers per hour and DEN is the density of vehicles per kilometer per lane. Equation 13 suggests a freeway free flow, including critical speeds of 98.62 kilometers per hour and 49.31 kilometers per hour, respectively. The critical speed is defined as the speed at maximum flow. For the principal arterial data, Equations 14 and 15 presented one of the two-regime models that provided the observed least root mean square of error 2.381:

$$\mathrm{TSP} = 58.21 \quad 0.81\ \mathrm{DEN}\ \text{for}\ \mathrm{DEN} \leq 18, \tag{14}$$

$$\mathrm{TSP} = 102.04 \quad 21.02\ \ln\ \mathrm{DEN}\ \text{for}\ \mathrm{DEN} > 18, \tag{15}$$

where the variable definition for Equations 14 and 15 is similar to Equation 13, Equations 14 and 15 suggest free flow and critical speeds of 58.21 and 21.02 kilometers per hour, respectively. More data could have improved the study results; however, the limited study resources confined the database to 216 sample points. Among the nine single and multiple regime types of speed and density models evaluated, Equations 13 to 15 were found superior, due to a smaller root mean square of errors. The selected models showed that for the study database, speed was sensitive to density, even at lower density values, on Iranian freeways and arterials.

CONGESTION MODEL CALIBRATION

For the selected descriptive variables, congestion intensity index models of Equations 10 to 12 were calibrated, respectively. The relevant speed information for free and capacity flows was derived from Equations 13 to 15. For comparison, intensity index models, based on the US highway capacity manual, HCM, were also developed. Among several HCM editions, freeway information from the 1985 HCM and arterial class I information from the 1994 HCM was found more compatible with Equations 13 to 15 [8-9]. The 1985 HCM freeway speeds for free and capacity flows are 96.6 kilometers per hour and 48.3 kilometers per hour, respectively. The 1994 HCM arterial class I speeds for free and capacity flows are 64.4 kilometers per hour and 20.9 kilometers per hour, respectively. Indeed, the 1994 HCM for arterial class I shows a range of free flow speeds of 35 to 45 miles per hour with a typical free flow speed of 40 miles per hour and, for arterial class II, a range of free flow speeds of 30 to 35 miles per hour, with a typical free flow speed of 33 miles per hour [9]. The 1994 freeway speed-flow curves are much flatter between free and capacity flow conditions than those reported in 1985, reflecting improved design and operation. The 1985 HCM speed-flow curves were found more comparable to Equation 13 and were, therefore, used. The 1994 HCM arterial class I speed information was found more comparable to Equations 14 and 15 than other arterial classes and was, therefore, used. For developing countries' congestion index modeling, the identification of relevant HCM traffic models was found to be the key to local usage and application.

Tables 1 and 2 show the calibration results for Equations 10 to 12, respectively. These models were developed, based on the free and capacity flow information derived from Equations 13 to 15. The signs of the calibrated parameters were logical and consistent, when it was expected that the higher the index, the higher the TRA, DRA, TRR and DLR, and the lower the TSP, respectively. To avoid calibration problems in the logarithmic form of Equation 11, zero

Table 1. Parameters of congestion models associated with TSP, TRA and DRA.

Model Parameters	Freeway, Iran	US Freeway, HCM 85	Arterial, Iran	US Arterial, HCM 94
$\mathbf{CII_{TSP}= k_{01} + k_1\ TSP}$:				
k_{01}:	10.0	10.0	7.823	7.402
k_1:	-0.101	-0.104	-0.134	-0.115
$\mathbf{CII_{TSP}=k_{02} + k_2 \ln TSP}$:				
k_{02}:	33.118	32.970	19.933	18.506
k_2:	-7.213	-7.213	-4.905	-4.443
$\mathbf{CII_{TSP}=k_{03} + 0.5k_3\ TSP^2}$:				
k_{03}:	6.667	6.667	5.748	5.589
k_3:	-0.0014	-0.0014	-0.0034	-0.0027
$\mathbf{CII_{TRA}=k_{01} + k_1\ TRA}$:				
k_{01}:	-5.0	-5.0	-2.823	-2.432
k_1:	8.217	8.050	2.738	2.578
$\mathbf{CII_{TRA}=k_{02} + k_2 \ln TRA}$:				
k_{02}:	3.583	3.435	-0.149	0.314
k_2:	7.213	7.213	4.905	4.443
$\mathbf{CII_{TRA}=k_{03} + 0.5k_3\ TRA^2}$:				
k_{03}:	-1.663	-1.667	-0.749	-0.589
k_3:	8.997	8.644	1.408	1.356
$\mathbf{CII_{DRA}=k_{01} + k_1\ DRA}$:				
k_{01}:	0.0	0.0	0.0	0.0
k_1:	8.217	8.050	2.738	2.578
$\mathbf{CII_{DRA}=k_{02} + k_2 \ln DRA}$:				
k_{02}:	6.378	6.304	3.964	3.883
k_2:	2.770	2.738	1.721	1.686
$\mathbf{CII_{DRA}=k_{03} + 0.5k_3\ DRA^2}$:				
k_{03}:	0.0	0.0	0.0	0.0
k_3:	27.052	25.932	2.999	2.659

values for free flow descriptive variables of DRA and DLR were replaced by 0.1. Some of the developed models provided a congestion intensity index beyond its assumed range of 0 to 10. For example, large values of TRA, DRA and TRR provided congestion intensity index values of more than 10 in some of the developed models. For traffic jam conditions, some of the developed models provided a congestion intensity index below 10. Not all the calibrated models covered and matched the assumed range of 0 to 10, similar to past studies [4,5]. For linear models of Equation 10, to exactly cover and match the congestion index range of 0 to 10, the descriptive variable at the capacity flow needed to occur at the mid point of its range. For the logarithmic models of Equation 11 to exactly match the congestion range of 0 to 10, the logarithm of the descriptive variable at capacity flow needed to occur at the mid point of its logarithm values range. Furthermore, only when the square of the capacity flow descriptive variable occurred at the mid point of its square values range, would the quadratic models of Equation 12 cover and match the index assumed range of 0 to 10. For models that did not match and cover the index assumed range of 0 to 10, two-regime models could have been developed for them. For realistic values of descriptive variables, the developed models of Tables 1 and 2 are applicable for congestion intensity index values remaining in the range of 0 to 10. For computed values below zero or above ten, the congestion intensity index should be replaced by 0 or 10, respectively.

The relationships between the HCM level of service and the developed congestion indices were studied. The results are summarized in Table 3. The table

Table 2. Parameters of the congestion index model associated with TRR and DLR.

Model Parameters	**Freeway, Iran**	**US Freeway, HCM 85**	**Arterial, Iran**	**US Arterial, HCM 94**
$\mathbf{CII_{TRR}=k_{01}+k_1}$ **TRR:**				
k_{01}:	-5.0	-5.0	-2.823	-2.402
k_1:	5.0	5.0	2.823	2.402
$\mathbf{CII_{TRR}=k_{02}+k_2 \ln}$ **TRR:**				
k_{02}:	0.0	0.0	0.0	0.0
k_2:	7.213	7.213	4.905	4.443
$\mathbf{CII_{TRR}=k_{03}+0.5k_3\ TRR^2}$**:**				
k_{03}:	-1.667	-1.667	-0.749	-0.589
k_3:	3.334	3.334	1.498	1.178
$\mathbf{CII_{DLR}=k_{01}+k_1}$ **DLR:**				
k_{01}:	0.0	0.0	0.0	0.0
k_1:	10.0	10.0	7.823	7.402
$\mathbf{CII_{DLR}=k_{02}+k_2 \ln}$ **DLR:**				
k_{02}:	7.153	7.153	6.207	6.029
k_2:	3.107	3.107	2.696	2.618
$\mathbf{CII_{DLR}=k_{03}+0.5k_3\ DLR^2}$**:**				
k_{03}:	0.0	0.0	0.0	0.0
k_3:	40.0	40.0	23.932	23.472

shows the freeway and arterial descriptive variables values for level of services A to E. These values were computed by using Equations 2 to 5, and 1985 HCM and 1994 HCM pertinent travel speed values [8,9]. Table 3 also shows the value of the delay rate index, $\mathrm{CII_{DRA}}$, based on the calibrated models of Table 1. For example, the $\mathrm{CII_{DRA}}$ of the linear model for LOS B for IR freeways is 1.07.

Highway delay is explicitly considered in DRA, TRR and DLR, and their associated indices were deemed more pertinent in addressing congestion intensity. Figures 1 to 3 show the three types of index model for Table 1 descriptive variable, DRA, similar to the delay rate index, DRI, suggested by Levinson and Lomax [4,5]. These figures show that the freeway and arterial index models for Iran are similar to the pertinent US index models. For a given delay rate, the developed models give a slightly higher congestion index for an Iranian facility, as compared with a similar US facility. Furthermore, for a given delay rate, the freeway congestion index models provide higher values than arterial congestion index models. The observed differences between the Iranian and US congestion models of Figures 1 to 3 are not significant. A quick response study, such as the one reported herein, will be conducive to the identification and testing of relevant HCM models as candidate surrogates for local usage. Figures 1 to 3 show that, for large values of delay rate, the upper limit of 10 should be replaced for the models' results as an index value. For US freeways and arterials, Levinson and Lomax recommended Figure 2 [4,5]. Using a multiplier, the study assumed that a congestion intensity index range of 0 to 10, can easily be modified to other desired ranges, such as 0 to 1, 0 to 20 or 0 to 100. Similar figures can be developed to show other index models of $\mathrm{CII_{TSP}}$, $\mathrm{CII_{TRA}}$, $\mathrm{CII_{TRR}}$ and $\mathrm{CII_{DLR}}$, as listed in Tables 1 and 2; however, space limitation prohibits their display herein. Figure 4

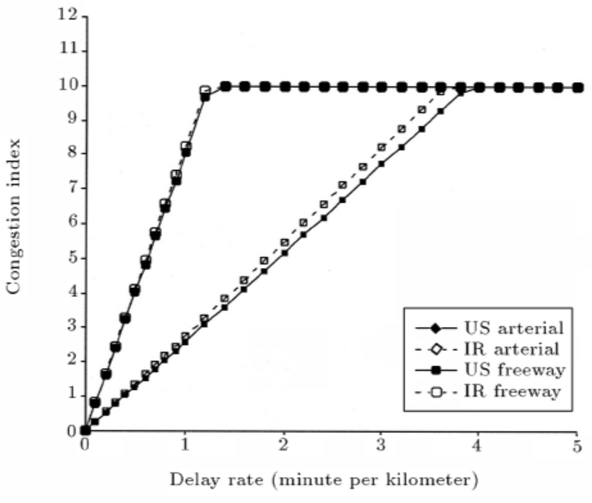

Figure 1. Linear congestion index models for delay rate.

Table 3. Descriptive variables and delay rate congestion indices.

Variable Name	LOS A	LOS B	LOS C	LOS D	LOS E
HCM 1985 Freeway Descriptive Variables					
TSP (kilometer per hour)	96.6	80.5	75.7	67.6	48.3
TRA (minute per kilometer)	0.62	0.75	0.79	0.89	1.24
DRA (minute per kilometer)	0.00	0.13	0.17	0.27	0.62
TRR (dimensionless)	1.00	1.20	1.28	1.43	2.00
DLR (dimensionless)	0.00	0.17	0.22	0.30	0.50
HCM 1994 Arterial Class I Descriptive Variables					
TSP (kilometer per hour)	56.4	45.1	35.4	27.4	20.9
TRA (minute per kilometer)	1.06	1.33	1.69	2.19	2.87
DRA (minute per kilometer)	0.13	0.40	0.76	1.26	1.94
TRR (dimensionless)	1.14	1.43	1.82	2.35	3.09
DLR (dimensionless)	0.13	0.30	0.45	0.58	0.68
IR Freeways					
CII_{DRA} (linear model)	0.00	1.07	1.40	2.22	5.09
CII_{DRA} (logarithmic model)	0.00	0.73	1.47	2.75	5.05
CII_{DRA} (quadratic model)	0.00	0.23	0.39	0.98	5.20
US Freeways					
CII_{DRA} (linear model)	0.00	1.05	1.37	2.17	5.00
CII_{DRA} (logarithmic model)	0.00	0.72	1.45	2.72	5.00
CII_{DRA} (quadratic model)	0.00	0.22	0.37	0.96	5.00
IR Arterials					
CII_{DRA} (linear model)	0.36	1.09	2.08	3.45	5.31
CII_{DRA} (logarithmic model)	0.45	2.39	3.49	4.36	5.10
CII_{DRA} (quadratic model)	0.03	0.24	0.87	2.38	5.64
US Arterials					
CII_{DRA} (linear model)	0.34	1.03	1.95	3.25	5.00
CII_{DRA} (logarithmic model)	0.44	2.34	3.42	4.27	5.00
CII_{DRA} (quadratic model)	0.03	0.21	0.77	2.11	5.00

shows the linear, logarithmic and quadratic index models associated with the delay rate for Iranian highway facilities. For any delay rate up to its value at capacity flow, the congestion index estimations, in increasing order, are for quadratic, linear and logarithmic forms, respectively. For capacity flow delay rates, all three types of developed model provide a congestion index of 5. For any delay rate more than its value at capacity flow, the congestion index estimations, in increasing order, are for logarithmic, linear and quadratic forms, respectively.

Based on the local traffic engineers' preference, any individual or combination of the Tables 1 and 2 developed models can be adapted and used in practice. Nevertheless, the co-relations among the descriptive variables, as are evident by Equations 1 to 4, make their combined usage less appealing. Based on a study, similar to Levinson and Lomax, the linear form of Equation 10 was found superior for congestion indices associated with TSP and DLR, and the logarithmic form of Equation 11 was found to be superior for congestion indices associated with TRA, DRA and TRR [4,5,7]. Nevertheless, further research is needed for more conclusive results regarding the functional forms. The simplicity of the linear models of Equation 10 makes them more appealing than the logarithmic and quadratic models of Equations 11 and 12. The selected five descriptive variables are all related to travel speed and time, and their interrelationships can easily be derived. Consequently, the selection of one functional form of Equations 10 to 12, for a given descriptive variable, mandates the superiority of a given functional form for other variables. For example, selection of the linear model of Equation 10

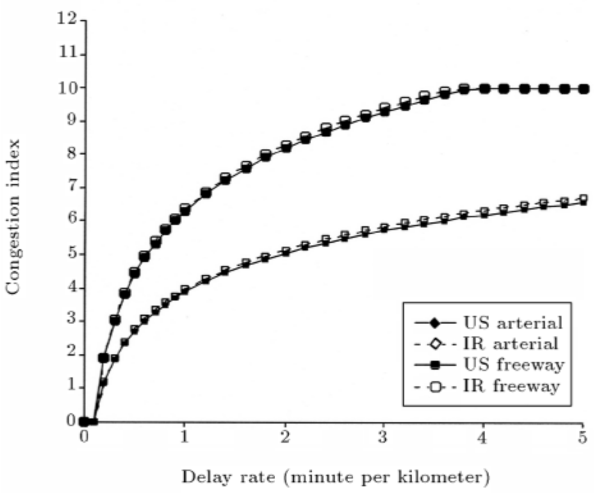

Figure 2. Logarithmic congestion index models for delay rate.

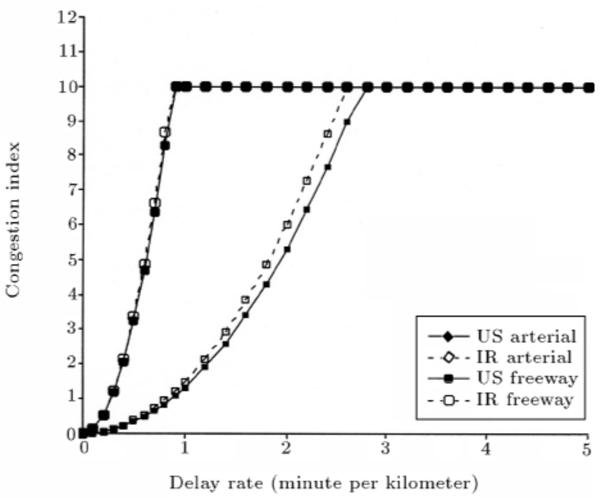

Figure 3. Quadratic congestion index models for delay rate.

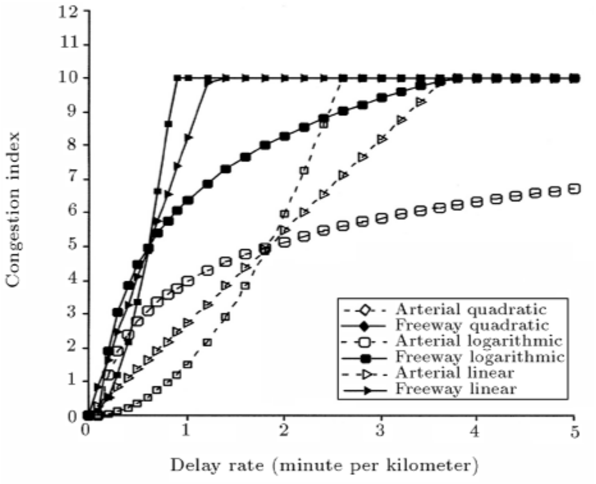

Figure 4. Comparison of linear, logarithmic and quadratic models.

for TSP, justifies the logarithmic model of Equation 11 for TRA rather than linear and quadratic forms.

Based on decision makers' judgments, any of the above mentioned index models can be adapted and used in practice. Similar to the HCM level of services of A to F, the indices, representing the congestion intensity status of the study area, can be used by transportation planners and traffic and highway engineers. Modification of highway facilities or operations can be granted if the indices exceed the pre-established thresholds.

OVERALL CONGESTION INDEX

To develop an overall congestion index, the preferences of a selected local group, with respect to developed indices, were assessed. First, the five descriptive variables, their relationships with each other and their associated indices were explained to 64 transportation professionals and university transportation engineering students. Then, they were asked to provide the relative importance of indices in describing highway traffic congestion. The persons were asked to show the relative importance of indices by percent, in such a way that their sum would equal 100. The results were used to obtain each of the indices' average weighting values. In order of decreasing importance, the indices were associated with TSP, DRA, DLR, TRR and TRA. Using the derived weights, an overall congestion index could be represented as:

$$\mathrm{OCII} = \sum w_i \mathrm{CII}_i, \tag{16}$$

where OCII is the overall congestion index, w_i is the weighting value of the ith congestion index and CII_i is the ith congestion index. Incorporating the average weights from surveyed preferences, Equation 16 became:

$$\mathrm{OCII} = 0.28\mathrm{CII}_{\mathrm{TSP}} + 0.13\mathrm{CII}_{\mathrm{TRA}} + 0.22\mathrm{CII}_{\mathrm{DRA}} + 0.16\mathrm{CII}_{\mathrm{TRR}} + 0.21\mathrm{CII}_{\mathrm{DLR}}. \tag{17}$$

Equation 17 provides an overall congestion index, based on the average weights of local preferences. Equations 1 to 4 can determine theoretical co-relations among the congestion indices; nevertheless, Equation 17 reflects 64 local transportation professionals and university transportation engineering students perceived weighting values of individual indices for a composite index. It is suggested, for congestion intensity assessment, that a composite measure is needed and desirable, even when there are co-relations among individual indices. Based on the total weights of 100, the stated average weights of 64 respondents, for $\mathrm{CII}_{\mathrm{TSP}}$, $\mathrm{CII}_{\mathrm{TRA}}$, $\mathrm{CII}_{\mathrm{DRA}}$, $\mathrm{CII}_{\mathrm{TRR}}$ and $\mathrm{CII}_{\mathrm{DLR}}$, were 28, 13, 22, 16 and 21, respectively. The OCII provides clues regarding the relative importance of developed indices, as perceived by the local community. Equations 1 to 4 showed co-relations among descriptive variables and, subsequently would provide clues regarding theoretical relations among their associated indices of $\mathrm{CII}_{\mathrm{TSP}}$, $\mathrm{CII}_{\mathrm{TRA}}$, $\mathrm{CII}_{\mathrm{DRA}}$, $\mathrm{CII}_{\mathrm{TRR}}$ and $\mathrm{CII}_{\mathrm{DLR}}$. On the other hand, OCII is an overall index developed, based on the respondents' relative stances and as they perceive individual indices.

CONCLUSIONS

In this study, highway congestion indices for a developing country in the Asia-Pacific region were developed and evaluated. The merit of this study remains in its suitability for developing countries with limited and scarce resources. The applied methodology presents a feasible and quick response approach for the congestion measurement of developing countries. The constrained technological and financial resources of developing countries make the application of developed country's methodologies most challenging. The study suggested that congestion indices were associated with five descriptive variables of travel speed, travel rate, delay rate, travel rate ratio and delay ratio, respectively. Both linear and nonlinear associations were developed between the congestion indices and descriptive variables, based on the relevant congestion rate of change assumptions. Assessment of congestion levels for the selected indices were based on freeway and arterial traffic data collection and analysis for the Iranian capital city of Tehran. Specific congestion levels were assessed to the index values under free and capacity flow conditions. Linear, logarithmic and quadratic congestion intensity index models were developed and evaluated. The developed index models were found similar to the HCM suggested models for the USA.

The calibrated congestion intensity index models were location specific and depended on input data; nevertheless the same methodology can be applied to any congestion index development. These indices have strong potential in traffic management. They can be used in congestion prevention and mitigation activities, and in the developing country's future intelligent transportation systems development. A quick response study, such as the one reported herein, is conducive to identification of relevant HCM models for local usage. An overall congestion index was also suggested as a complimentary or an alternative measure for congestion intensity assessment and evaluation, although the explained relationships among its descriptive variables make it less appealing. The overall congestion index was developed on the basis of local preferences, and can be utilized if a composite measure is needed.

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