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Travel Demand Management for Sustainable Urban Transport in Kuala Lumpur: Operation and Energy Consumption Issues

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Abstract

A number of South-East Asian cities are experiencing rapid growth in car ownership and overall transportation demand in the context of relatively low fuel and road tax along with land use patterns that encourage private automobile trips. To address these challenges, sustainable transport initiatives, which often include travel demand management (TDM), are increasingly being promoted at the city level. This paper examines the effectiveness of TDM on reducing road traffic congestion and energy consumption in the city of Kuala Lumpur, Malaysia. In this and similar cities that experience periods of severe traffic congestion, predicting the impacts of TDM can be complicated by the unstable nature of existing traffic flows. A new approach and tool are presented here that enable planners and decision makers to analyze a single or combinations of TDM options such as carpooling, bus/BRT lane, road pricing and increased transit ridership along a specific road corridor to arrive at a plan that satisfies specified limits on congestion. The model can also estimate energy consumption under the planned scenario and thus helps to implement sustainable energy initiatives for the transport sector. The paper will focus on the implications of TDM options for congestion and energy consumption in Kuala Lumpur.

Keywords: *Travel demand management; sustainable transport; energy consumption and congestion*

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INTRODUCTION

A number of Southeast Asian cities such as Kuala Lumpur, Seoul, Bangkok and Jakarta have experienced rapid motorization [1–3] throughout the last decade with an increasing prospect of unsustainable congestion and energy consumption in the near future. This phenomenon is replicated in much of the developing world where the number of motor vehicles is increasing at more than 10% a year resulting in a doubling every seven years [1]. A study produced by the World Bank [4] has compiled estimates for the travel times and costs associated with urban transportation for cities in both developed and developing economies. Five of the surveyed cities with populations over 4 million (Bucharest, Jakarta, Kinshasa, Lagos, and Manila), have average one-way commute times of greater than one and one-quarter hours [5]. A recent study by Hossain and Kennedy [6] confirms similar average travel times of more than one hour for commuters in Kuala Lumpur. The economic costs of congestion were also estimated in the World Bank study [7], with cities such as Dakar and Buenos Aires expending more than 3% of their GDP due to delays and difficulties in conducting business. For Bangkok, congestion costs were estimated at 1 to 6% of GDP. For the developing cities reported in the study, the total external costs due to urban transport tended to range between 5 and 10% of GDP. In terms of petroleum consumption, the transport sector is by far the largest consumer, accounting for 58% of total final consumption of petroleum products globally and 45% in Southeast Asia [8]. For nations that are net importers of petroleum (or on a course to become one soon), the combination of rising oil prices and rapid growth in the transport sector has the potential to disrupt their fiscal stability.

In Kuala Lumpur, the number of car and freight vehicle registrations has experienced a compounded growth rate of over 9% during the period from 1986–2003 [9]. In 2004, the transportation sector was the biggest energy user, consuming approximately 41% of the nation's energy demand – an increase of 9% from the previous year [10]. The sector's share of petroleum consumption was even higher at 67% of all petroleum products. Rising demand compounded with fuel subsidies and a sustained increase in oil prices has set the Malaysian transport sector on an unsustainable course; potentially posing a threat to national energy security [6]. In an attempt to cater to this increasing automobile trip demand, a number of highways/expressways have been constructed totaling over 300 km in length during the last two decades with additional highways under development or in the planning stage even now [9]. It is understood that such highway expansion needs huge investment and may not be the most cost-effective or equitable means for providing sufficient mobility and accessibility for the population. Even with the ongoing large investments in road infrastructure, the continued increase in automobile trips, which currently comprise 84% of all vehicular trips, has stretched much of the current capacity to its limit. Traffic congestion, particularly on the main arterials and streets in the city center, is pervasive for most hours of the day. A relevant question is how these unsustainable trends in the urban transport sector can be controlled in a pragmatic way.

Travel demand management (TDM) can be an effective tool to achieve multiple interrelated criteria for sustainable urban transport, such as reduced congestion, improved environmental impact and lower energy consumption. TDM options such as carpooling, bus/BRT lanes, road pricing and increased transit ridership can influence the temporal, spatial and modal distribution of travel demand and as such can have a significant impact on the traffic situation in a corridor. Considering the claim that transportation researchers and planners have missed the big picture view of TDM implications for the transport sector [11], it is important to enhance our toolset for assessing multiple TDM options simultaneously. We must also evaluate the impacts that these options have at an operational level (e.g., localized congestion and energy consumption). It is important that the assessment of TDM options can be incorporated into the planning process as well; particularly in relation to the now ubiquitous efforts to achieve some form of "sustainable urban transport" among urban and transport planners. A number of useful software tools are available for national or regional level transportation planning such as TRANSCAD, EMME/2, Cube Voyager and TRansDec. For energy planning, similar tools are available to support long-term national or regional scenario planning (see for example: SEI, 2006). While these tools deal with sector level planning, fewer supporting tools are available to assess sustainable planning options (e.g., TDM) at an operational level; yet, they are very much needed. For example, a tool to estimate the impact that either road widening or segregated bus lanes would have on congestion and energy consumption along a given corridor would not only assist planners in choosing the appropriate project, but would also help them to communicate with the relevant authorities and politicians that may be the drivers behind efforts towards achieving a sustainable urban transport system. In this present work, the authors propose a spreadsheet-based scenario planning tool to evaluate the implications of TDM options with respect to sustainability issues for individual urban corridors. Numerous definitions for sustainable urban transport have been proposed by various researchers and organizations. According to one definition [12], sustainable transport concerns the means to move people, goods and information in ways that minimize any adverse environmental impact and have positive consequences for the economy and society. For our present purpose, we take a narrowly defined version of sustainability that considers only two operational criteria for road traffic along a city corridor – congestion and energy consumption. With this definition as our basis, we introduce a modeling methodology and tool that can be used to assess the sustainability of various TDM options.

The authors continue by describing travel demand characteristics of urban arterial corridors of Kuala Lumpur. Continuous, real-time data of vehicle flow has been collected from a number of observation cameras with on-site image processing software. Then is introduced the modeling methodology using the observed data to develop the model mechanisms and estimate model parameters. Thereafter is introduced a set of planning scenarios, followed by a discussion of the results and typical model applications.

TRAVEL DEMAND AND FLOW CHARACTERISTICS

For transportation planning studies, detailed information on current travel demand can be extremely helpful in generating a baseline from which various TDM options can be assessed. In the present study, the authors have used data collected by the Kuala Lumpur Intelligent Transport Information System (ITIS), which consists of 726 automatic incident detection (AID) cameras recently installed throughout the road network of Kuala Lumpur for incident detection and traffic data collection. The video imaging processor of the AID system produces operational data which are stored at the Kuala Lumpur Traffic Management Centre (TMC) at a 3-minute resolution. The processed data includes vehicle volume, average speed, headway and other variables, all classified into heavy, medium and light vehicles and distinguished according to individual lanes.

Weekday samples of volume (vphpl) and speed (kmph) profiles are shown for the middle lane along three typical urban sections in Kuala Lumpur in Figures 1 through 3. Each weekday in July 1–31, 2006, was split into 480 three-minute intervals. The profiles show a dot for the mean value and the 5th through the 95th percentile, marked by vertical lines, for each 3-minute interval. The first two figures illustrate inbound and outbound traffic on the same section, while the third plot shows inbound traffic at a different location. For the inbound sections, the peak demand occurs between 6:00 am and 9:00 am, and outbound demand peaks around 17:00–20:00. The morning inbound peak tends to ramp up very quickly, while the evening outbound peak follows relatively high volumes sustained throughout the day. High standard deviations for both speed and volume tend to occur during high demand periods, revealing that both volume and speed are less stable when demand is high.

Two important observations can be drawn from these profiles: (1) the peak mean volume rarely exceeds 2000 vphpl, and (2) periods of high trip demand do not always correspond to high values for the mean vehicle flow volume. The former is clearly shown by the volume profiles, while the latter requires some elaboration. On an inbound corridor, the greatest trip demand is likely to occur during the morning peak. However, as evidenced clearly in Figure 1, the average volume and speed observed between 6 and 9 am drop to 37and 73% of their maximum values, respectively. The drop in the two profiles can be explained by frequent occurrences of traffic congestion and flow breakdown during this peak period. The fact that flow volume can drop significantly in a high demand period and that speed and volume can decrease or increase in unison is usually not captured by the majority of traditional planning models.

In the modeling framework proposed here, the influence of flow breakdown on the estimated vehicle volumes is reconciled by formalizing the distinction between mean vehicle flow volume and vehicular trip demand. The mean *demand* profile, which is the basic input to the proposed model, corresponds to an *ideal* vehicle volume that would be achieved at a section of road during a certain time period under a stable flow situation; whereas the mean *volume* profile represents the volumes achieved after considering actual flow conditions. In the absence of detailed real flow data, like in the present case, the demand profile can be obtained from a traditional demand forecasting exercise. In a planning context, demand profiles are much easier and more intuitive to generate, especially for long-term projections utilizing the four-step planning model, while predicting actual volume is more difficult as it requires some knowledge of how the actual flow conditions will evolve.

Using field data, the authors distinguish between demand and volume by first classifying all data points into either stable or unstable flow regimes. Figure 4 illustrates both a schematic diagram of stable and unstable flow on a speed-volume plot, and observed values from field measurements along Ipoh Road. The stable and unstable flow regimes are distinguished by establishing a flow breakdown speed (s_b) from the reported speed-volume diagram of the section. The observed values for this section closely follow the conceptual speed-flow diagram. One reason for the clear distinction between stable and unstable values in the observed data is the negligible influence from any nearby intersections at this location. If the flow followed a signalized pattern, it would be more difficult to clearly classify between stable and unstable flow. Hence, the model and discussion here are most relevant for corridors with uninfluenced flow.

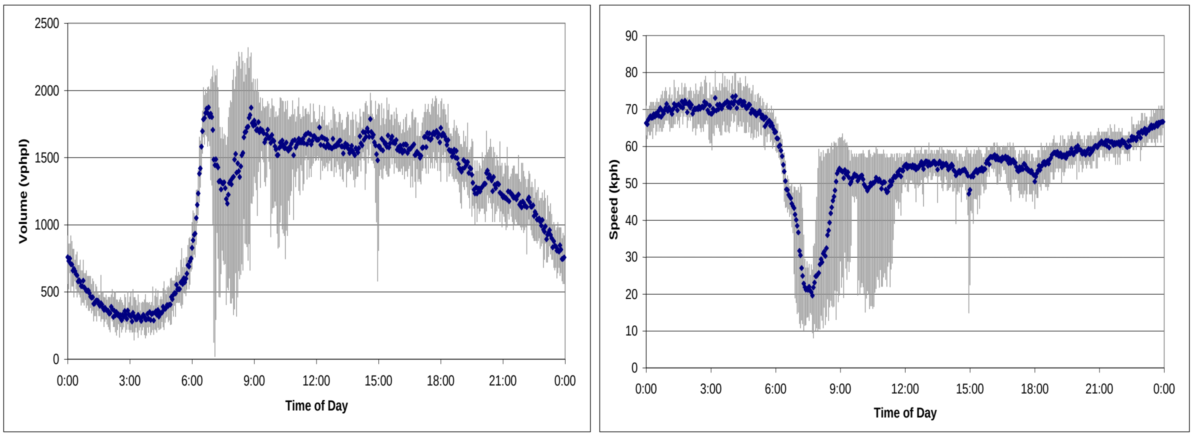

Fig. 1: *Volume and Speed Profile for Ipoh Road – Uninfluenced Inbound Section.*

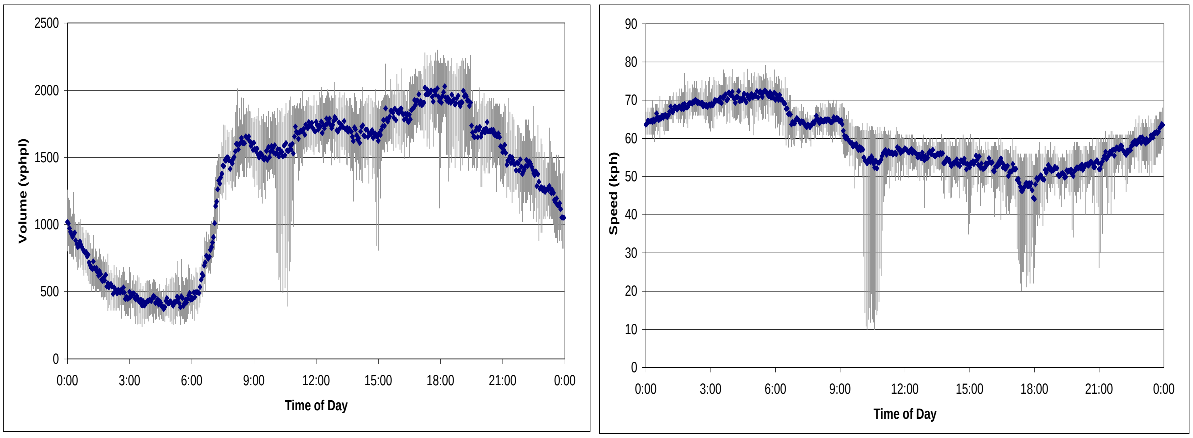

Fig. 2: *Volume and Speed Profiles for Ipoh Road – Uninfluenced, Outbound Section.*

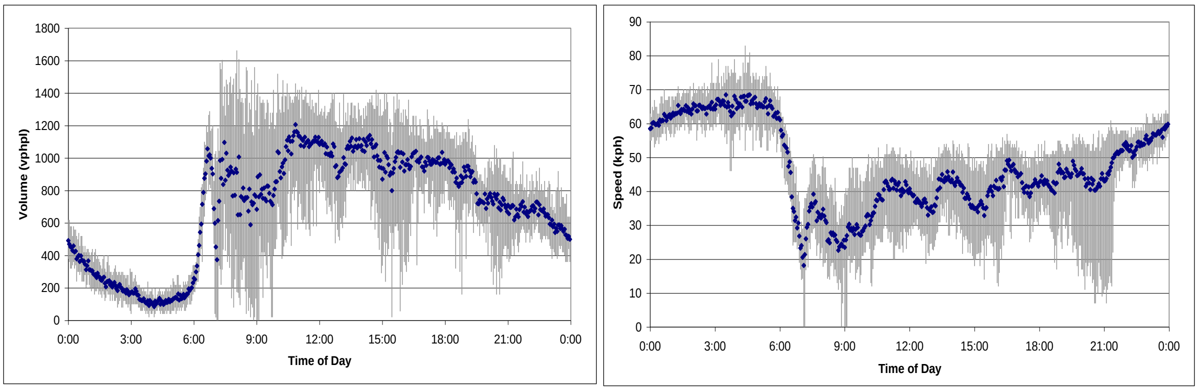

Fig. 3: *Volume and Speed Profiles for Cheras Road – Uninfluenced, Inbound Section.*

Using the average speed as an indicator for stable or unstable flow, we can now derive two different volume profiles – one comprising only stable volumes and one for all volumes. The former will be considered as a proxy for the demand profile, while the latter is the realized volume profile. Figure 5 shows the two profiles plotted together for a weekday on a single lane of Ipoh Road. One can see here that during the morning peak period, the average stable volume reaches its maximum value, while the average realized volume drops due to occasional unstable flow. The purpose of the present model development is to incorporate this phenomenon into an assessment of TDM options along a single corridor.

METHODOLOGY

A sustainable transport and energy planning (STEP) modeling tool has been developed to assess the impact of TDM options on congestion and energy consumption along a traffic corridor that frequently experiences unstable flow. A schematic representation of model mechanism alongside the inputs and outputs is shown in Figure 6. There are four groups of inputs required to use this model: (i) corridor travel demand, (ii) flow model parameters, (iii) scenario settings, and (iv) fuel consumptions curves.

Travel demand in this study is represented by an hourly profile comprising the average number of vehicular trips passing through the corridor for each hour of the day. The corridor is assumed to have only one entry and one exit point. As explained previously, the onset of flow breakdown will reduce the volume of vehicles and the number of vehicular trips that the corridor could support under stable conditions. Hence, travel demand, as defined here, will be estimated by considering only stable flow conditions. Such a profile could be generated through field observations – neglecting any measurements taken during flow breakdown – or from projections based on various planning scenarios. If possible, distinct profiles should be used for weekdays, Saturday and Sunday. The remaining input categories will be described in detail in the following subsections..

The two model outputs provide a measure of the corridor's operational and energy sustainability, with the former represented by the amount of unmet travel demand due to flow breakdown and the latter by the total energy consumption due to trip demand for that corridor. The total energy consumption is derived from an estimate of the fuel consumed by all vehicles traveling the corridor length; and can also include an energy value for the unmet travel demand. If one considers that all unmet trips are diverted to an alternate route, and that these diverted trips take neither more nor less time than a trip along the original corridor (during a flow breakdown situation), then it would be reasonable to assume that each diverted trip consumes as much fuel as an actual trip along the corridor. This approach has been used here to estimate an energy consumption value for the unmet demand.

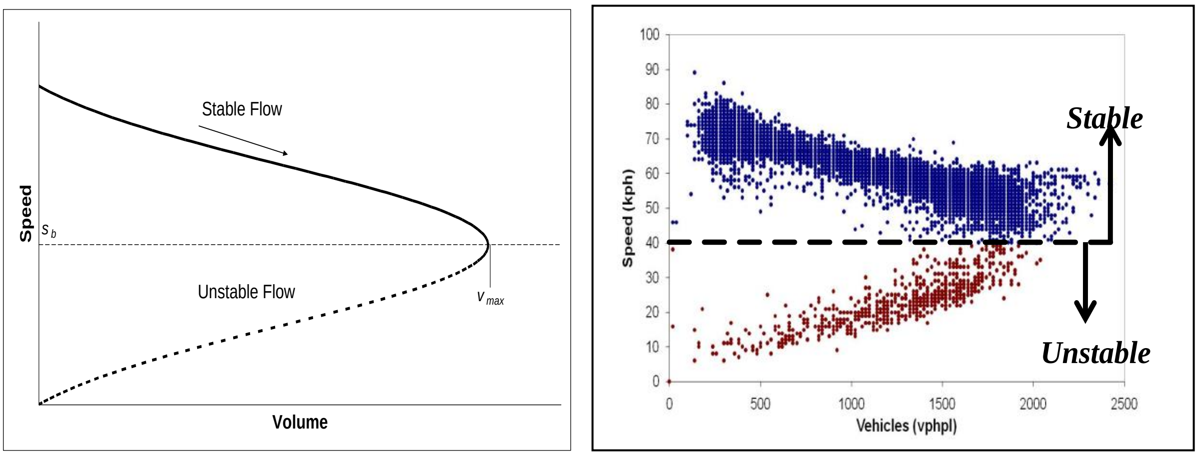

Fig. 4: *Schematic Diagram and Observed Values Showing Stable and Unstable Flow Regimes for a Single Inbound Lane on Ipoh Road.*

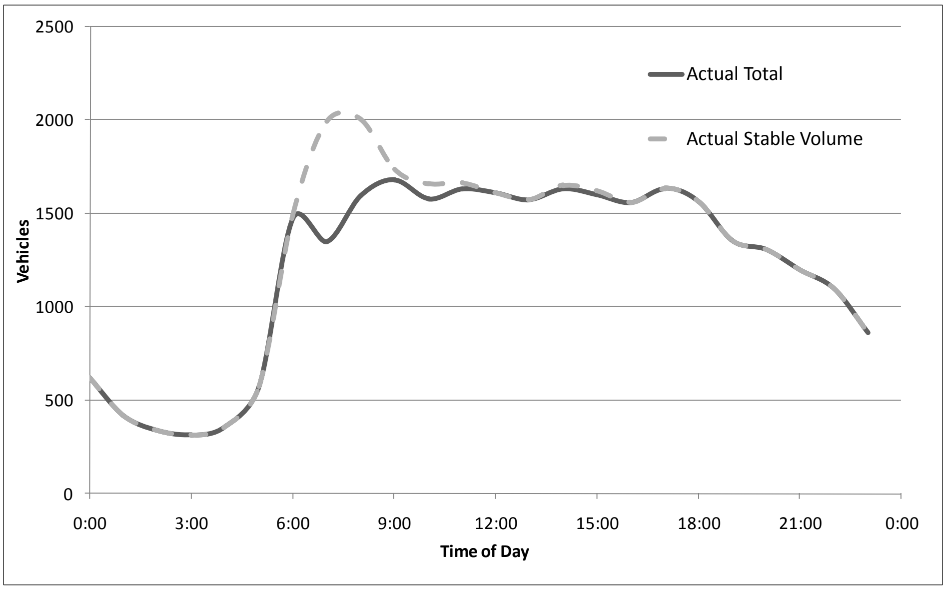

Fig. 5: *Stable and Actual Volume Profiles for a Single Inbound Lane on Ipoh Road.*

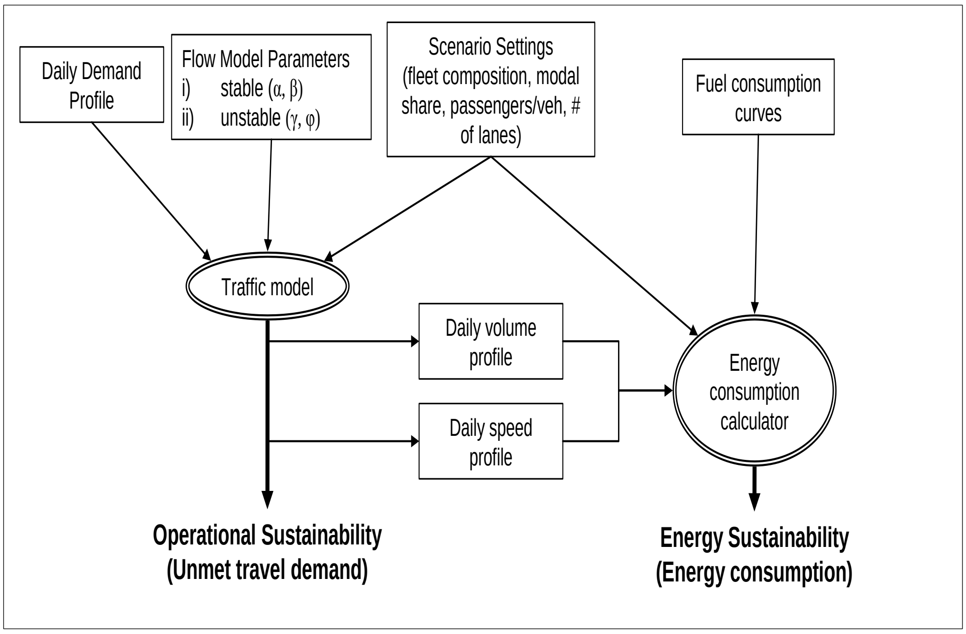

Fig. 6: *STEP Model Information Flow Diagram.*

Traffic Model

The objective of the traffic model is to estimate an hourly profile of realized vehicle volumes and travel times based on inputs of hourly travel demand and various scenario parameters. The traffic model is actually a two-state model that estimates volumes and travel times separately for stable and unstable flow conditions. An expected value for the total travel time is found by summing stable and unstable travel times weighted by the probability of residing in either state. If the flow has a non-zero probability of becoming unstable during a given time interval, then the realized volumes will fall short of the demand (shortfalls are recorded as unmet demand), otherwise volume and demand will be equal and only the stable flow model will be used.

For stable flow conditions, a standard BPR [13] volume-delay function is used to estimate the travel time. Here, the travel time (t) increases monotonically with increasing vehicle volume (v). A free flow travel time (t_f) must be estimated, along with the road or lane capacity (c) and the model parameters α and β.

For the present case, the lane capacity and free flow travel time are set equal to the 95th percentile of observed values for vehicle volume and travel time, respectively.

$$t = t_f \left(1 + \beta \left(\frac{v}{c}\right)^{\alpha}\right) \tag{1}$$

In cases of flow breakdown, a macroscopic relationship between flow volume and travel time is very difficult to determine. Yet, in many cities with constrained road space, the phenomenon of flow breakdown is commonly experienced. Hence, using the classic volume-delay function alone would tend to underestimate travel times (and fuel consumption) by neglecting the added time loss during severe congestion. If the classic model assumes a fixed capacity limit, it may also overestimate the sustainable level of demand, since this capacity will not be attainable during flow breakdown. This problem may be quite serious in the context of planning scenarios that project an increase in travel demand a number of years into future. If the occurrence of flow breakdown becomes more frequent during peak periods, an increase in demand would correspond to a drop in realized traffic volumes. This phenomenon has been readily observable in data collected for Kuala Lumpur which show heavily loaded corridors exhibiting a drop in average speed and volume during peak periods due to a more frequent occurrence of flow breakdown.

Unstable Flow

Under incident free situations, flow breakdown may occur due to speed variances among drivers, e.g., too small of a head way and the presence of wild drivers. From speed and volume data obtained from urban corridors in Kuala Lumpur, it was observed that the periods with frequent occurrences of flow breakdown also tended to exhibit high traffic volumes during intermittent intervals of stable flow; implying a possible relationship between stable volumes (i.e., travel demand) and flow breakdown. Data also revealed that unstable flow is characterized by erratic values for speed and volume, which persist until stable flow is reestablished. Due to the unpredictable nature of speed and volume during unstable conditions, we do not attempt to determine the unstable analogue of the volume-delay function for stable flow. Instead, we utilize the observed relationship between travel demand and flow breakdown to estimate the likelihood that flow breakdown will occur during each period of the day and then assign mean values of volume and speed to represent these unstable periods.

Relationship between Flow Breakdown and Stable Volume

In order to determine a relationship between the stable volume and the likelihood of flow breakdown, the authors first choose to represent likelihood as the frequency of occurrence. For the one-month of data along the inbound section of Ipoh Road (Figure 1), is calculated the frequency of flow breakdown for each 3-minute period of the day. The flow breakdown frequency ($0 < f_{fb} < 1$) was then compared to the average of all stable volumes observed over the same 3-minute period (v_s). It should be noted that stable flow and flow breakdown are mutually exclusive. Therefore, if flow breakdown occurred for 25% of the samples for a given period, this value ($f_{fb} = 0.25$) was then plotted against an average of the stable volumes from the remaining 75% of the sample. Figure 7 shows the frequency of flow breakdown plotted against average stable volume. Both linear and logistic curves were fit to the data. A slight improvement was found using a logistic curve with an R^2 value of 0.811 compared to 0.727 for a linear model. An approximate relationship between the frequency of flow breakdown and the stable volume for a given period in the 24-hour profile can be expressed as follows,

$$f_{fb} = \frac{1}{1 + e^{-(\gamma v_s + \phi)}} \tag{2}$$

The model parameter values are $\gamma = 0.0108$ and $\varphi = -21.9$. A logistic curve is conceptually appealing for this relationship. At low travel demand, it is very unlikely (although not impossible) for flow breakdown to occur. As travel demand increases, the frequency of flow breakdown increases smoothly – in this case with a steep slope near the high flow region. Beyond this flow zone, the breakdown frequency curve flattens again indicating that the breakdown frequency has almost saturated nearing 100%.

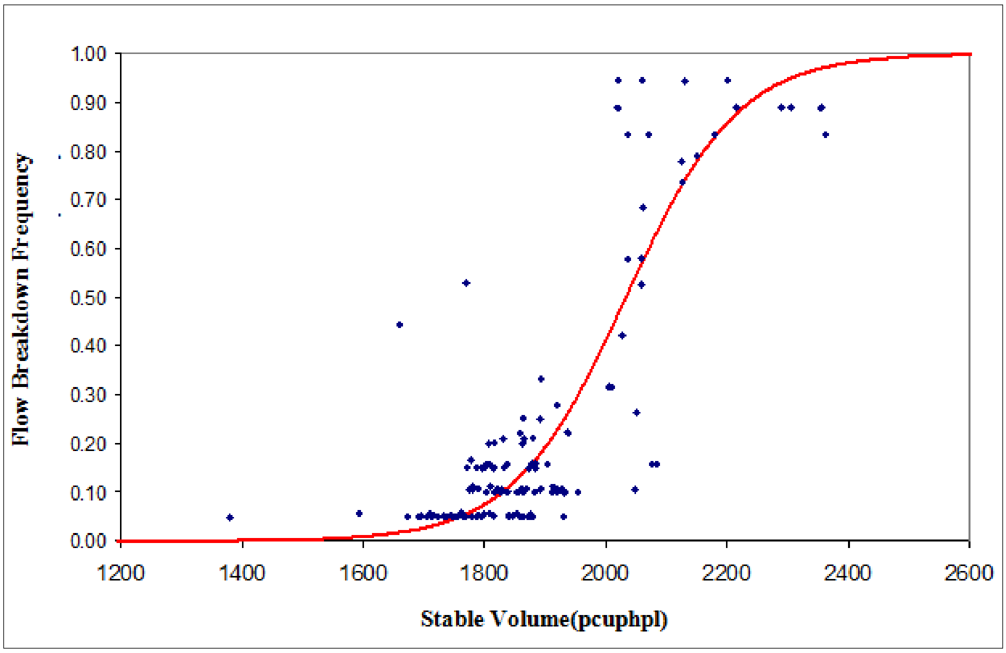

Fig. 7: *Relationship between Stable Volume and Frequency of Flow Breakdown. Each Point Represents One 3-minute Period from the 24-hour Profile Averaged over a One Month Period.*

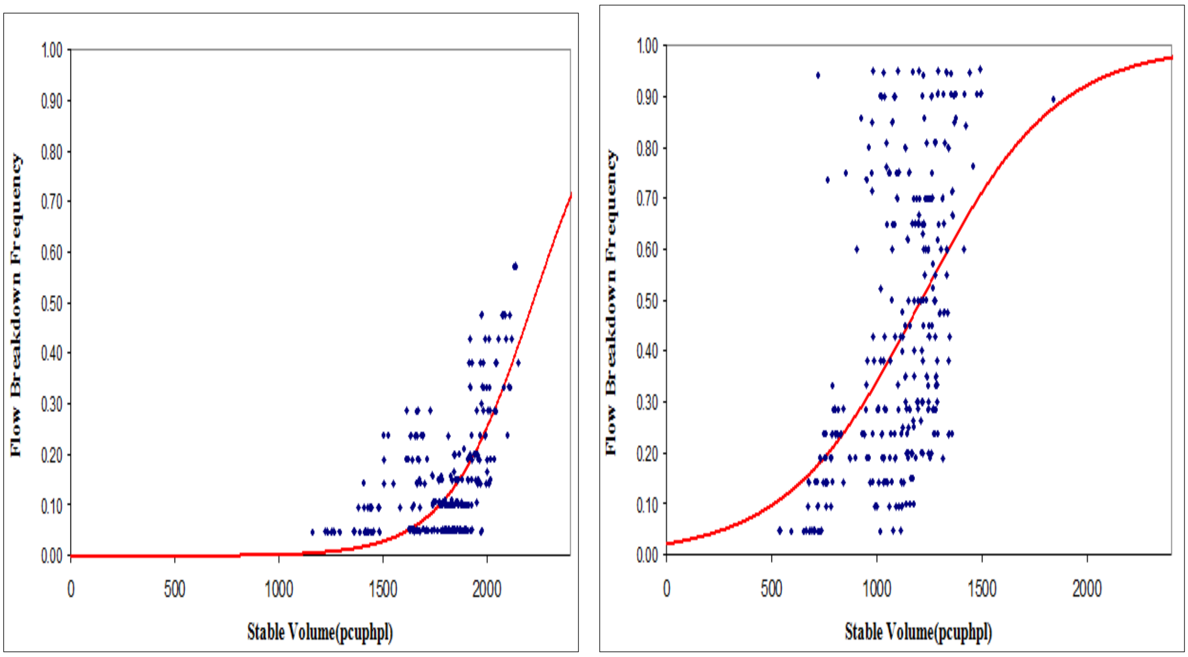

Fig. 8: *Frequency of Flow Breakdown vs. Stable Vehicle Volumes (in pcuplph) for (a) Outbound Section of Ipoh Road and (b) Inbound Section of Cheras Road.*

Table 1: *Summary of Model Parameters for Stable and Unstable Flow.*

	Stable flow				**Unstable flow**		
Section	A	β	c	R^2	γ	ϕ	R^2
Ipoh Road (inbound)	1.21	0.374	1990	0.683	0.0108	-21.9	0.811
Ipoh Road (outbound)	1.26	0.354	2110	0.580	0.00167	-5.65	0.412
Cheras Road (inbound)	0.900	0.492	1350	0.661	0.0031	-3.79	0.399

A similar logistic curve can be derived for the other sections for which volume and speed data were shown in Figures 2 and 3. The outbound section of Ipoh Road (Figure 2) clearly does not experience unstable conditions as frequently as the inbound section, which can be seen from Figure 8a, as only the lower section of the logistic curve is populated with observed data. A logistic curve also provides a better fit with an R^2 value of 0.412 compared to 0.260 for a linear relationship, with model parameter values: $\gamma = 0.00167$ and $\varphi = -5.65$. For the inbound section of Cheras Road in Figure 8b, the data are more scattered vertically. A logistic fit still provides a slight advantage over a linear model, with an R^2 value of 0.399 compared to 0.391, with model parameter values: $\gamma = 0.00313$ and $\varphi = -3.79$. Due to the narrow difference in the closeness of fit for the different model types, it is possible that a linear model may be more appropriate in some cases.

The stable and unstable model parameters for the three sections illustrated in Figures 1–3 are summarized in Table 1, along with the R^2 values for the regression lines. The capacity, *c*, is shown in units of pcu per lane.

Two-State Flow Model

By combining the stable and unstable flow models, we arrive at the proposed two-state flow model. The actual vehicle volume profile (v_a) can be calculated by summing the stable and unstable profiles, weighted by the frequency of occurrence of each respective flow regime.

$$v_a = \left(1 - f_{fb}\right) v_s + f_{fb} v_u, \tag{3}$$

which can also be written as

$$v_a = v_s + \frac{v_u - v_s}{1 + e^{-(\gamma v_s + \phi)}} \tag{4}$$

One consequence of using this model is that a maximum capacity limit is implicitly defined by the model parameters. According to Eq. (4), as v_s increases, which represents an increase in demand, the actual volume will increase up until a maximum value determined by v_u, γ and φ. As v_s continues to increase, the actual volume will drop and asymptotically approach the mean unstable volume, v_u, which would occur at 100% flow breakdown.

The actual travel time can be calculated in a similar fashion through a weighted sum of the stable and unstable travel times. The demand profile, which is determined from estimates of the average stable volume during each period of the day, is input into the classic volume-delay function to determine the mean travel time for stable flow. For unstable flow, an estimate of the mean travel time during flow breakdown is used.

Calculating Energy Consumption

Vehicle technology is the main factor dictating fuel economy along with other factors such as vehicle maintenance, age and loading, driving pattern and driving cycle. Tong *et al.* [14] report on an analysis of on-road vehicle speed, emission, and fuel consumption data collected by four instrumented vehicles in the city of Hong Kong. Considering four standard driving modes as acceleration, cruising, deceleration, and idling, their study found that the transient driving modes (i.e., acceleration and deceleration) were more polluting than steady-speed driving. Although their study provides fuel economy models based on real field data, it is based on only four vehicle types driven on the unique network of the city of Hong Kong.

A general established trend to obtain fuel economy data is to test vehicles driven by professional drivers in controlled laboratory conditions following certain standard driving cycles [15] and adjust the results to account for differences between the controlled laboratory conditions and real world situations. The U.S. Department of Energy and Environmental Protection Agency (EPA) as well as the Vehicle Certification Agency (VCA) of the UK both compile an annual database of standard fuel economy data for various new vehicles each year [16, 17]. The VCA database includes fuel economy data on Malaysian models and is therefore used in the present study. The above driving cycles (EPA and EC) are established to represent “typical” driving patterns for either highway or city driving. As such they can only estimate fuel consumption at an aggregate level of driving, but cannot be used to estimate the fuel consumption for a trip that varies from the typical pattern. In the present study, utilizing a fixed driving cycle to estimate fuel consumption would not be appropriate, as we would then not be able to account for changes in vehicle speed. Instead, we rely on results from a study by Rakha et al (2000), in which they showed that for the same average speed, one can observe widely different instantaneous speed and acceleration profiles, each resulting in different fuel consumption and emission levels. In their study [18, 19], the authors used results from a series of dynamometer tests [20] to derive a relationship between fuel consumption, vehicle speed and acceleration. Similar functions were also derived for emissions. For an average "composite" vehicle, four curves were presented that relate instantaneous fuel consumption to instantaneous vehicle speed for four driving modes, respectively. These are rapid acceleration (1.8 m/s^2), moderate acceleration (0.9 m/s^2), steady speed, and deceleration (−0.9 m/s^2). For the purpose of the present study, we take a weighted average of the four curves according to the frequency that each mode occurs during the EC driving cycle. The EC driving cycle is used as there has not yet been a driving cycle constructed for Malaysian conditions. The resulting single curve, shown in Figure 1, gives a more realistic representation of fuel consumption for a given *average* speed. To calibrate the curve for a specific vehicle type, all values are multiplied by a correction factor, which is the ratio of the average fuel consumption for the vehicle type in question over the fuel consumption for the composite vehicle in the study by Rakha *et al.* [18]. With this approach, the present model can readily accommodate any new fuel consumption curve for other vehicle types, which might be available in future. By estimating the operating speed from the volume-delay function for stable flow and the mean speed for unstable flow, the fuel consumption can be estimated for the different vehicle types in the stream for all periods of the day.

STUDY SCENARIOS

The STEP model was applied to examine the effects that trip reduction, increased use of public transport, and carpooling could have on energy consumption and operational sustainability. The TDM options have been grouped into the scenarios shown in Table 2. All scenarios, including a baseline scenario denoted as a business-as-usual (BAU) path, are projected from the base year of 2006 until the year 2020 with fixed values for trip growth rate, modal share, and passengers per vehicle. It is important to remark that the modal share shown here represents the share of *demanded* trips by each mode, not necessarily the share of realized trips. If the section experiences unstable flow, then the actual number of trips will be less than what is demanded and an assumption must therefore be made about how these unmet trips are allocated among the different modes. In the present analysis, we have assumed that only cars have the flexibility to switch to another route and all unmet trips are allocated to this mode. Hence, the actual trips realized by the other modes (i.e., MDV, truck, and bus) must be equal to the demanded trips. In terms of the modal share of realized trips (not shown here), flow breakdown will cause the cars to switch to another route thereby reducing the car modal share for this section and increasing the modal share of the MDVs, trucks and buses.

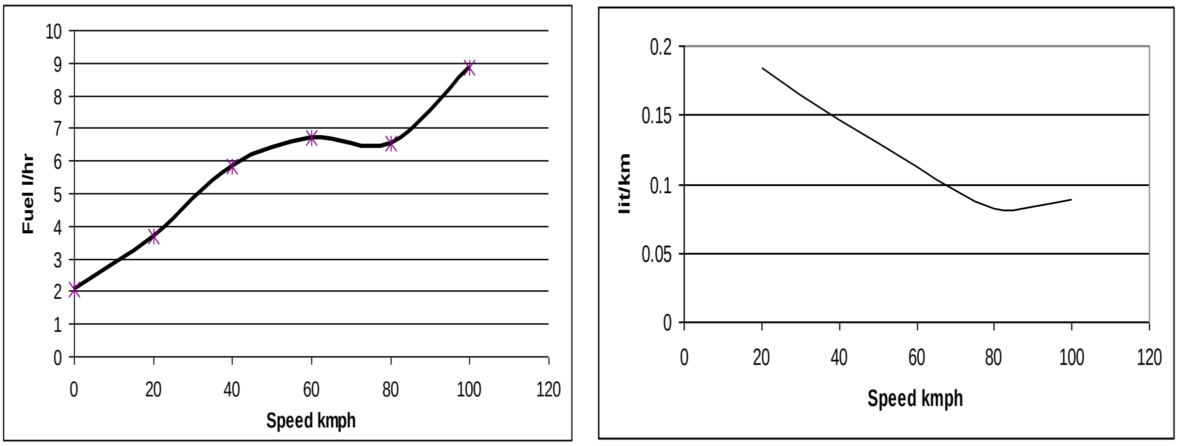

Fig. 9: *Calibrated Fuel Consumption vs. Speed for Light Vehicles.*

Table 2: *Scenario Descriptions.*

Scenario	**Trip growth rate (%/year)**	**Modal share (% of trip demand)**	**Passengers per vehicle**
S1 - Business as usual (BAU)			
	2.73	77 (car) 8 (MDV) 4 (truck) 11 (bus)	1.3 (car) 1.5 (MDV) 2 (truck) 20 (bus)
S2 – Trip demand reduction (TDR)			
S2A – Slow growth	1.0	Same as S1	Same as S1
S2B – No growth	0.0	Same as S1	Same as S1
S2C – Negative growth	−1.0	Same as S1	Same as S1
S3 – Bus rapid transit (BRT)			
S3A – Low BRT usage	2.73	48 (car) 8 (MDV) 4 (truck) 40 (bus)	1.3 (car) 1.5 (MDV) 2 (truck) 80 (bus)
S3B – Moderate BRT usage	2.73	38 (car) 8 (MDV) 4 (truck) 50 (bus)	1.3 (car) 1.5 (MDV) 2 (truck) 100 (bus)
S3C – High BRT usage	2.73	28 (car) 8 (MDV) 4 (truck) 60 (bus)	1.3 (car) 1.5 (MDV) 2 (truck) 120 (bus)
S4 - Carpooling			
S4A – Small response	2.73	77 (car) 8 (MDV) 4 (truck) 11 (bus)	1.5 (car) 1.5 (MDV) 2 (truck) 20 (bus)
S4B – Moderate response	2.73	77 (car) 8 (MDV) 4 (truck) 11 (bus)	2.0 (car) 1.5 (MDV) 2 (truck) 20 (bus)
S4C – Large response	2.73	77 (car) 8 (MDV) 4 (truck) 11 (bus)	2.5 (car) 1.5 (MDV) 2 (truck) 20 (bus)

All scenarios have some form of bus transport plying in the corridor. However, for the BRT options (S3), the bus has a much higher capacity, a greater modal share, and has taken over exclusive use of one of the existing lanes (i.e., there is one less lane available for the other modes). In S1, S2, and S4, the bus shares road space with the other modes.

RESULTS

Results will be shown here for an application of the STEP model on a single inbound section of Jalan Cheras – a heavily used corridor on the periphery of Kuala Lumpur. The section under examination has three lanes and is 1 km in length. Base year data covering a period from July 1–31, 2006 was obtained from a single camera and AID system located at the site. There is currently mixed traffic across all lanes.

Operational Sustainability

The operational sustainability of the different scenarios is best illustrated by plotting the realized volume profiles in comparison with the trip demand profile. Figure 10 illustrates this plot with the trip demand as the uppermost curve and with the business-as-usual profile (S1) as the lowest curve; all other scenarios lie within this envelope except S2A and S2C showing lower realized volumes in the lean periods. This is due to fewer trips i.e. flow volume in lean periods because of lower/negative trip growth rate for these scenarios. However, during higher demand periods, S2A and S2C achieve a higher realized trip volume than S1, due to their lower demand, which results in a reduced number of flow breakdowns as compared to S1. The area between the trip demand curve and each scenario curve represents each scenario's unmet trip demand. The scenario with the lowest unmet demand is the high response carpooling scenario (S4C) with 2.5 passengers per car. Only a small amount of unmet demand is evident during the morning peak. The high usage BRT scenario, with 60% modal share by bus (S3C), performs second best, again with the unmet demand concentrated in the morning peak period. A notable difference between the carpooling and BRT scenarios is that the carpooling scenarios, particularly S4A and S4B, perform very poorly during the morning peak period with a higher number of unmet trips during this period compared to off-peak. The BRT scenarios, however, all provide the highest number of trips during the peak period. The reason for the difference is that the BRT is not affected by peak congestion as it runs in a segregated lane, unlike the carpooling vehicles. Hence, the BRT is still able to meet the target of 60% of trips during peak, while the hourly number of carpooling trips is reduced due to congestion. Travel times for vehicles in the unrestricted lanes (i.e., not including the BRT lane) are shown for scenarios 1, 2, 3, and 4 in Figure 11. The low-usage BRT scenario (S3A) and the BAU case (S1) hit the maximum travel time from approximately 6 am to 6 pm, revealing that the flow in the mixed traffic lanes would be almost continuously unstable at this level of vehicle demand. The base year (2006) travel times are also shown here, with only the high response carpooling scenario (S4C) and trip demand reduction (S2C) achieving lower travel times than the base year. The mixed traffic lanes in the BRT scenarios perform relatively poorly in terms of travel times, as compared to carpooling, because the implementation of the BRT has reduced the number of lanes available for cars, MDVs and trucks from three to two. Therefore, if reducing travel times for non-bus trips is of high priority, then an effective carpooling program could be more effective than a BRT option that takes over an existing lane. Yet, it is not travel times for non-bus trips alone that may be the best criteria. The following section will illustrate the effect of the different scenarios on another important indicator - energy consumption.

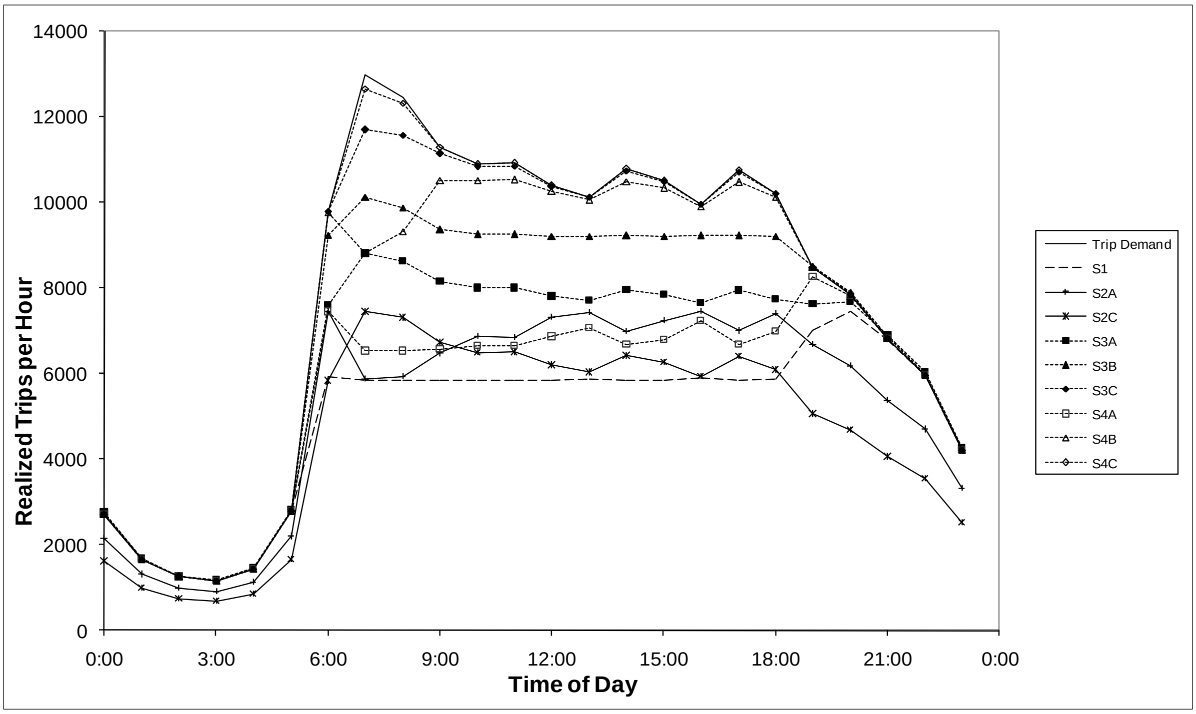

***Fig. 10:** Realized Volume Profiles for Scenarios 1, 2, 3 and 4. Gap between Trip Demand and a Given Volume Profile Represents Unmet Demand in the Year 2020.*

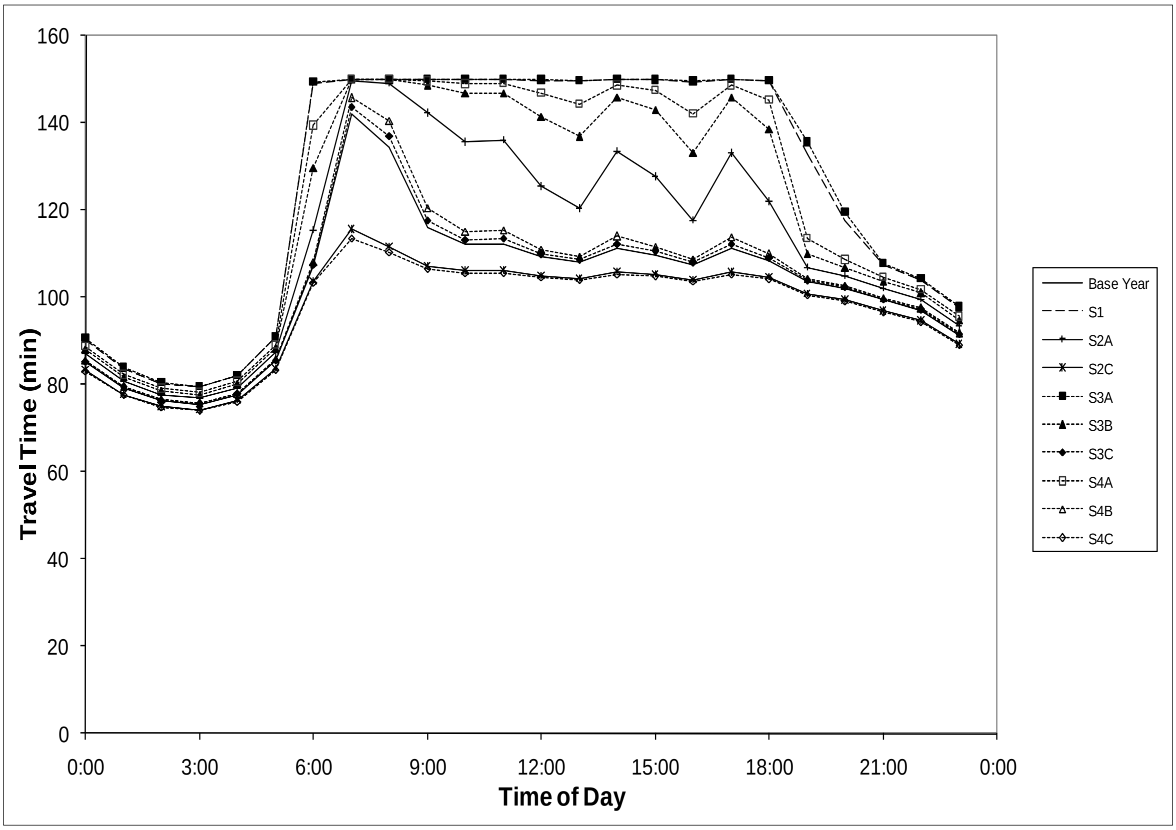

Fig. 11: *Projected Travel Time Profiles for Scenarios 1, 2, 3, and 4 in the Year 2020. Scenario S1 and S3A are at Maximum Travel Times for the Entire Period between approximately 6 am–7 pm due to a Continuous State of Flow Breakdown.*

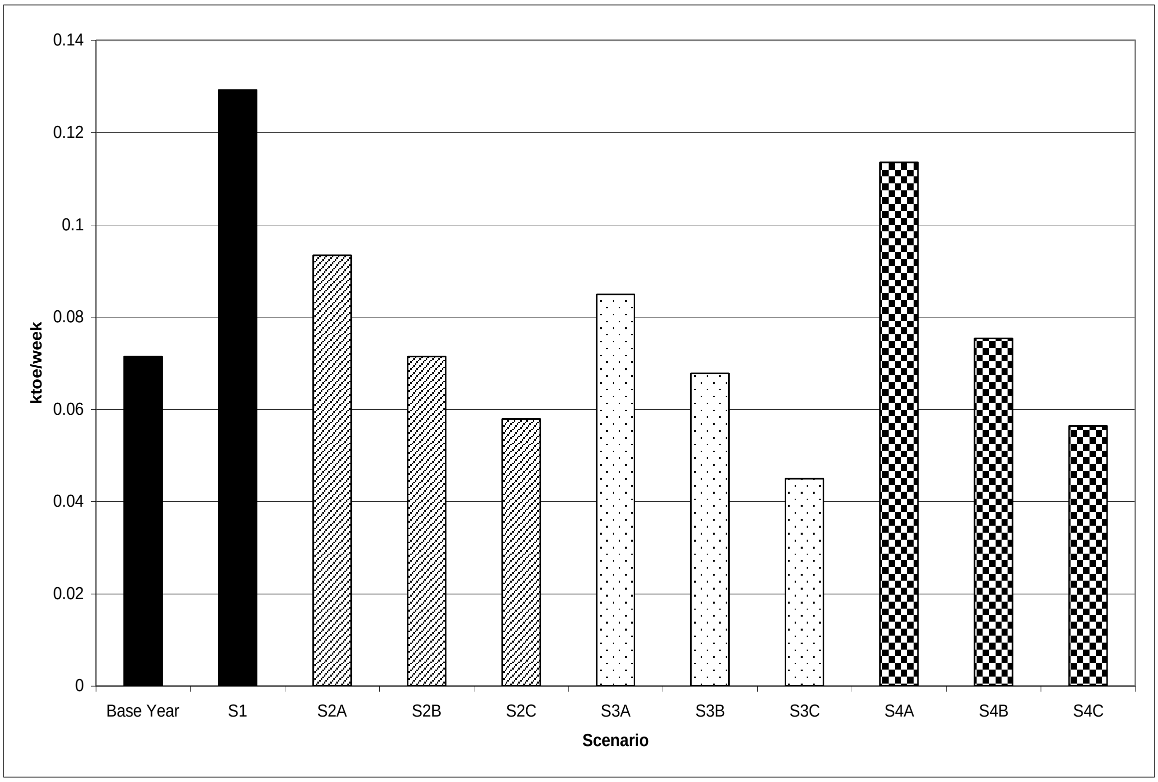

Fig. 12: *Total Energy Consumption (ktoe/week) for all Scenarios. Base Year is 2006, while all others are Projections for 2020.*

Energy Consumption

The estimated energy consumption depends on the number, type, and speed of vehicles, as well as the amount of unmet demand. As explained earlier, unmet trips are considered as diverted trips for the purpose of the energy calculation, with each diverted trip consuming an equal amount of energy as the realized trips during the same period.

Figure 12 shows the total energy consumption across all four scenarios and their sub-scenarios, including a reduction in trip demand (S2). By this measure, the BRT scenario is the most effective in reducing energy consumption. Considering the percentage reduction from the BAU case (S1) for the best sub-scenarios, negative trip growth (−1% per annum) (S2C) results in a 55% reduction, a BRT modal share of 60% (S3C) yields a 65% reduction, and carpooling at 2.5 passengers per vehicle (S4C) results in a 56% reduction. It is interesting to note that both the carpooling and BRT scenarios, at the parameter values chosen here, outperform the trip demand reduction scenario in terms of energy consumption. In other words, there is substantial room for a reduction in energy consumption without having any negative impact on the number of trips.

CONCLUDING COMMENTS

This study presents a new methodology and tool for interactive and simultaneous evaluation of multiple TDM options in achieving reductions in traffic congestion and energy consumption for an urban corridor. As these goals relate closely to principles of sustainable urban transport, the tool can be used to provide quantitative support for the development of urban transport policy. The model is specifically developed for corridors that experience significant congestion and unstable vehicular flow at the present time or according to future demand projections. Traffic congestion is estimated based on travel delay with additional information on demand that is either unmet or diverted to a different route. The methodology for calculating energy consumption has incorporated recent work relating fuel consumption to instantaneous vehicle speed and acceleration, thereby allowing the projections of travel delay to influence fuel consumption.

The emphasis has been on estimating the impacts of TDM options at an operational level, which can help to reduce some of the uncertainty in planning for a sustainable urban transportation system. Further study is needed to increase the accuracy of the fuel consumption estimation, especially in assessing the influence of speed and acceleration for a wider sample of vehicles. Further work could also be performed in extending the model’s capability to estimate the vehicular emissions load along the roadway corridor.

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