Australasian Transport Research Forum 2016 Proceedings
16 – 18 November 2016, Melbourne, Australia
Publication website: http://www.atrf.info

Piecewise Linear Regression: A Statistical Method for the Analysis of the Relationship between Traffic Signal Parameters and Air Pollutant Emissions

Christina Ng[1], Susilawati Susilawati[1], Irene Chew Mei Leng[1]

[1]School of Engineering, Monash University Sunway Campus, Malaysia.

[1]School of Engineering, Monash University Sunway Campus, Malaysia.

[1]School of Engineering, Monash University Sunway Campus, Malaysia.

Email for correspondence: susilawati@monash.edu

Abstract

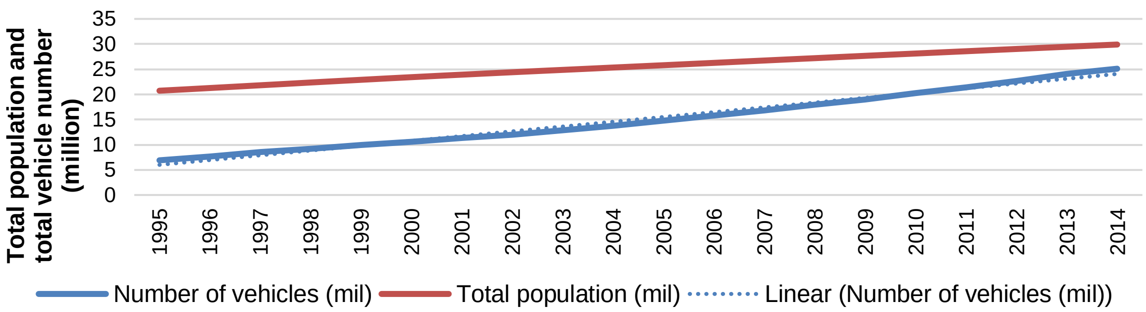
On-road emissions from urban traffic during interrupted and congested flow conditions are often higher compared to free-flow traffic condition and are often influenced by changes in accelerating and decelerating speed due to frequent stop-and-go. In this study, we present linear regression models to investigate effects of congestion on traffic emissions along an arterial road and used regression models to derive analytical expressions separating free-flow traffic conditions with congested conditions. The regression models use traffic demands and degree of saturation as explanatory variables. Correlation of emission rates with traffic parameters (cycle length, the degree of saturation, and flows) was investigated at a range of conditions extending from under-saturated to oversaturated traffic flows. Data for calibrating these models are obtained from the application of Sidra Intersection, a micro-analytical software. A comparison of the proposed models to similar information contained in the Highway Capacity Manual marked similarity to the point of saturation and suggested an additional relationship with emission rates. Results confirmed that the relationship between the amount of air pollutant emission and traffic flow as well as the degree of saturation shown a piecewise linear relationship with significant differences in slopes separated by breakpoints. Moreover, regression results suggested that degree of saturation for the point of saturation is proposed for volume-to-capacity (v/c) ratio values at 0.99, indicating that for all volumes, the change in emission of CO_2 occurs around this value. As the efforts at integrating traffic simulation models and emission models have become a fast-evolving research area, the findings of this study will set up a solid and extensive application of simulation optimisation in sustainable traffic planning, operations, and management as well as reducing emissions at urban areas.

Keywords: Urban traffic, Air pollution, Traffic signal, Carbon dioxide

1. Introduction

Passenger cars in most countries make up a major portion of traffic fleets on urban roads (Ministry of Transport 2015). Rapid growth and expansion of urban centres further increases traffic demand, which in most cities have exceeded the road capacities, which results in frequent congestion events (Barth & Boriboonsomsin 2008; Ge et al. 2015). Malaysia, for example, bucks the percentage of car ownership with 93%, placing third in the world. Since 1995, the trend of car ownership in Malaysia has increased gradually and almost surpassed population rate (see Figure 1) (Ministry of Transport 2015; The World Bank 2015). They are known to have the highest incidence of multiple car ownership globally with about half of the households having more than one car (Nielsen 2014). Such growth in car ownership, not only affects the traffic performance and mobility of travellers, but may also increase vehicle emissions (CO, CO_2. VOCs, HCs, NO_x, PM, etc.). Emissions has also been observed higher at signalised intersections as vehicles spend more time in idling or crawling, and undergoing numerous acceleration and deceleration events (Coelho et al. 2009). International Energy Agency (2015) consolidated statistics shows that Malaysia road transport sector contributed 191.4 million tonne of CO_2 in 2012 and 207.2 million tonnes in 2013, indicating a 289.02% (Year 2012) and 321,1% (Year 3013) increment from 1990. Impacts due to vehicle emissions have been receiving increasing attention, and recent epidemiological studies show elevated health risks especially for children and pregnant women who commutes or living near roadways (Slezakova et al. 2013; Zhang & Batterman 2013). This has further generate a sense of urgency to study emissions emitted from vehicles in order to develop effective emission control strategies.

Figure 1: Trend of number of vehicles and population in Malaysia (Ministry of Transport 2015; The World Bank 2015).



2. Literature Review

The study of air pollutant emissions that occur during congestion periods have received limited attention. A few studies have been conducted (Anderson et al. 1996; Sjodin et al. 1998; De Vlieger et al. 2000; Frey et al. 2001). Sjodin et al. (1998) has shown an increase in emissions up to four-fold with congestion, as compared to uncongested conditions. De Vlieger et al. (2000) indicated that vehicle emissions and fuel consumption rates of passenger cars increased by 10-20% during rush hour comparing to smooth flow conditions, and the changes in emission and fuel consumption rates also varied by vehicle and road type. Frey et al. (2001) used on-board measurements and found 50% increase in emissions during congestion. In a similar study, Zhang et al. (2011) compared the work zone and rush-hour congestion with free-flow traffic and found higher emissions during the transitional phase from free-flow traffic to congested condition. Their study, however, used speed-acceleration profiles by car floating technique, which represents an average scenario of a limited number of vehicles on roads and may be underestimating actual emissions. Overall, the available pas studies suggested that congestion elevates vehicle emissions, however, there is still considerable uncertainty in quantifying these changes, as a result of limited field testing and varying traffic conditions.

The estimation of vehicle emissions have been tested on macroscopic emission models, i.e. MOBILE 6, that are based on standardised driving cycles , representing typical driving patterns along major road types such as freeways, arterials, ramps, and local roads (EPA 2003). Here, air pollutant emissions are estimated from measurements on test vehicles subjected to specific driving cycles simulated by a chassis dynamometer. Emissions associated with specific traffic conditions are then derived by taking into account on the differences between the desired average traffic speed and other environmental parameters, and those associated with standardised driving cycle. It is also known that MOBILE 6.2 and other macroscopic emission models are widely used in emission inventory and other regional applications. However, the use of such models has been criticised since they do not consider the full range of driving patterns that may be encountered when estimating emissions for specific roadways (Joumard et al. 2000). Since emission rates are obtained based on average speed at fixed driving cycles, there could have limited ability to consider alternate driving patterns. While different driving cycles can produce identical average speeds, emissions depend strongly on the specific acceleration and deceleration patterns. Thus, actual emissions can be significantly underestimated since acceleration, deceleration and aggressive driving patterns are not fully represented (Joumard et al. 2000). Emissions also requires better quantification at signalised intersections, especially considering the time spend idling at this area during congestion. According also to EPA (2003), MOBILE 6 does not use results of idling tests, and idling results are based on emission rates measured only at a speed of 4 km/h. The real-world accuracy of this approach is thus, unknown. Hence, macroscopic models may inaccurately estimate emissions at congested traffic conditions (Smit 2006).

Microscopic models, such as CMEM (Scora & Barth 2006) and MOVES (EPA 2009), provide an alternative option to estimate vehicle emissions in congested and non-congested driving condition. There are able to estimate emissions for temporal scales ranging from second to hours, and for specific vehicles as well as vehicle fleets. Besides, these models can explicitly account for idling, accelerating, cruising and decelerating engine operating conditions, and are able to simulate second-by-second speed and power fluctuations of vehicles on a road network. Temporal and vehicular aggregations are necessary since these models are designed to predict emissions for vehicle categories (Scora & Barth 2006). Microscopic models can be applied to both conventional and greenhouse air pollutants, and have been used to model impacts of traffic congestion as well (Barth & Boriboonsomsin 2008). On the downside, microscopic models tend to be data and computationally intensive when modelling large areas with complex road networks.

Although emissions have been previously examined with experimental and modelling approaches under congested conditions, information regarding the prediction of emission at the point of saturation remains unknown. The majority of these models have not been designed to account for the transition from under-saturated to oversaturated traffic condition. Furthermore, the thresholds that may lead to specific ranges for the relationship of traffic characteristics with emission has yet been identified. The lack of publications regarding congestion-related emissions is an important gap, especially given the growing frequency and severity of congestion. The transition of emission changes from under-saturated to oversaturated traffic flow should not be taken lightly as a significant difference in the level of emission will greatly contribute to the rise in air pollution. Urban traffic-flow pattern in real-world driving is unpredictable, especially during peak hours. Most times, it changes between interrupted and congested conditions, where traffic density and degree of saturation are higher, impacting emissions considerably.

The research effort presented in this paper addresses two objectives. The first objective is to investigate effects of congestion on traffic emissions on an arterial signalised intersection using Sidra Intersection software. Effects of congestion are done by means of varying traffic volume with degree of saturation. The second objective is to derive analytical expressions for the amount of air pollutant emission as the function of traffic characteristics and signal parameters using piecewise linear regression. Here, we identified the critical points that separated under-saturated and oversaturated traffic flow, where a significant increase in emission rate can be observed at this point. The scope of this paper is limited to greenhouse gasses (GHG) emissions, in particular, carbon dioxide (CO_2) because it is part of a large constituent of transport's GHG emissions. Globally, the transport sector's contribution to total CO_2 emitted from fuel combustion is 23%, of which road traffic is responsible for almost three-quarters (International Energy Agency (IEA) 2015). Also to be noted that the scope covers traffic simulation and regression analysis. Field measurement of traffic emission is not taken into account for this paper and will be verified in future study. To address the research objectives as discussed, the next section describes the methodology on working piecewise linear model towards case study application. Finally, the main conclusions of the paper are presented after the presentation of a review of the evaluation results.

3. Methodology

To achieve the objectives of this research, the methodology is developed by first understanding the concept of piecewise linear model which will be used to derive a set of analytical expression to estimate the CO_2 emission rate. The details of emission models found in traffic simulation software will be discussed before applying it in a case study.

3.1. Piecewise Linear Model

Piecewise linear models are “broken-stick” models, where two or more lines joined at unknown points, called “breakpoint (s)”, representing the threshold(s). Breakpoints are the values of x where the slope of the linear function start changes. At this point, the regression function may be defined as discontinuous, but it can be written in a continuous form. When a breakpoint exists, e.g. at x = c, the model can be written as follows:

$$y = a_1 + b_1x \qquad \text{for } x \le c \qquad \text{(Equation 1)}$$

$$y = a_2 + b_2x \qquad \text{for } x > c.$$

In order for the regression function to be continuous at the breakpoint, the two equations for y need to be equal at the breakpoint (when x = c):

$$a_1 + b_1c = a_2 + b_2c. \qquad \text{(Equation 2)}$$

Solving for one of the parameters in terms of the others by rearranging the equation above:

$$a_2 = a_1 + c\,(b_1 - b_2). \qquad \text{(Equation 3)}$$

Then by replacing a_2 with the equation above, the result is a piecewise regression model that is continuous at x = c:

$$y = a_1 + b_1\,x \qquad \text{for } x \le c \qquad \text{(Equation 4)}$$

$$y = [a_1 + c\,(b_1 - b_2)] + b_2\,x \qquad \text{for } x > c.$$

This model has been used and verified in traffic-related and emission studies for air and noise pollutants (De Coensel et al. 2007). Numerous traffic variables have been identified to fit emissions data such as vehicle speed (Cappiello et al. 2002), vehicle specific power (Huai et al. 2005; Zheng & Zhang 2015), delay (Lv 2012) and even meteorological variables (Zhang & Batterman 2010). Their studies have shown meaningful relationships derived from emissions and traffic flow parameter. This suggests that piecewise linear relationship performed reasonably well in emission estimation for traffic studies.

As discussed in the objectives, we used the method of piecewise linear regression as a tool to analyse the relationship between traffic emissions and flow, as well as the degree of saturation. Hence, to facilitate the testing of this method, a statistical software RStudio, that is capable of performing piecewise linear regression and applying statistical tests to the regression results is made available. With RStudio, there are essentially two methods that can be used to fit this model to the data: (i) brute force iterative approaches (Crawley 2012) and (ii) the ‘segmented’ package (Muggeo 2003,2008). Using these approaches allows us to statistically estimate the breakpoint for the change in slope. This model is fitted by using the segmented function in the segmented package found as an extension to R (R Core Team 2014). The procedure of ‘segmented’ package uses maximum likelihood to fit different parameterization of a model. One major difference found between these methods is that, the ‘segmented’ approach constraints the segments to be (nearly) continuous, which is not seen in the iterative approach.

With this, a simplified setting consisting of an urban arterial road with several consecutive signalised intersections will be considered, and through the simulation of a range of scenarios, the influence of traffic demands and signal timing parameters on air pollutant emissions will be investigated (no air pollutant dispersion modelling is considered). Given what is understood about this model, an assumption is made for the relationship between flows and emission as a continuous function. To perform this theory, a sample script is presented for one of the intersections in Appendices.

3.2. Emission Model from Analytical Traffic Model

The rate of CO_2 emissions has been calibrated with different models in previous studies and various traffic variables have been tested (Barth & Boriboonsomsin 2008; Afotey et al. 2013). In this study, we use Sidra Intersection, version 6.1 to generate emission under a range of traffic conditions. Sidra is a micro-analytical software which is widely used in traffic engineering for the study and evaluation of a lane-by-lane analysis on different intersection types. It uses traffic models coupled with an iterative approximation method to provide estimates of measures of effectiveness (MoE) such as intersection capacity, total delay, queue lengths and emission levels (Akçelik et al. 2012). Sidra method emphasises the consistency of capacity and provides detailed information on the performance of all lanes, turning movements and approach legs, as well as the intersection as a whole. Unlike any other software, Sidra provides reliable and consistent MoE output, which is an important property to make the proposed model a viable one and also easy to establish (Akçelik et al. 2012).

For emission modelling, Sidra Intersection estimates the cost, energy and air pollution implications of intersection design using an instantaneous four-mode elemental model with detailed acceleration, deceleration, idling and cruise elements. This drive-cycle (modal analysis) method coupled with a power-based vehicle model is used to estimate operating cost, fuel consumption, greenhouse gas (CO_2) and pollutant (NOx, CO, HC) emissions in order to assess the environmental impacts of traffic congestion. The key advantage of the power-based model is that it relates fuel consumption to the fundamentals of vehicle motion which are relatively easy to calibrate using an instrumented vehicle (Akçelik et al. 2012). The emission model in Sidra has been calibrated and validated for Australian vehicles (Biggs & Akcelik 1986) as well as modern vehicle fleet (Akçelik et al. 2012). The instantaneous model in Akçelik et al. (2012) model estimates the fuel consumption rate (mL/s) as a value per unit time measured at any instant during the trip which is expressed as a function of the tractive power required by the vehicle:

$$f_t = \alpha + \beta_1 P_T + [\beta_2 a P_1]_{a>0} \quad \text{for } P_T > 0 \qquad \text{(Equation 5)}$$

$$= \alpha \quad \text{for } P_T < 0$$

$$P_T = \min(P_{max}, P_C + P_I + P_g)$$

$$P_C = b_1 v + b_2 v^3$$

$$P_I = M_V a v / 1000$$

$$P_G = 9.81\, M_V (G/100)\, v / 1000$$

$$\alpha = f_i / 3600$$

where f_t is the instantaneous fuel consumption rate (mL/s); P_T is the total tractive power (kilowatts, kW); P_{max} is the maximum engine power (kW); P_C is the cruise component of total power (kW); P_I is the inertia component of total power (kW); P_G is the grade component of total power (kW); R_T is the total tractive force (kilonewtons, kN) required to drive the vehicle; G is the percentage of road grade; M_v is the total mass of vehicle (kg) including occupants and any other load; v is the instantaneous speed (m/s); a is the instantaneous acceleration rate (m/s^2); α is the constant idle fuel consumption rate (mL/h), which applies to all modes of driving (as an estimate of fuel used to maintain engine operation); $f_i = 3600\ \alpha$; b_1 is the parameter of vehicle associated with rolling resistance (kN); b_2 is the parameter for vehicle associated with aerodynamic drag ($kN/(m/s)^2$); β_1 is the efficiency parameter which relates fuel consumption with the total power provided by the engine, also can be shown as fuel consumption per unit of energy (mL/kJ or g/kJ); and β_2 is the efficiency parameter which relates fuel consumption during positive acceleration to the product of acceleration rate and inertia (mL/(kJ.m/s^2) or g/(kJ.m/s^2)).

The instantaneous CO_2 emission rate (g/s as a value per unit time) are estimated directly from the instantaneous fuel consumption rate:

$$f_t(CO_2) = f_{CO2}\, f_t(fuel) \qquad \text{(Equation 6)}$$

where f_t(fuel) is the fuel consumption rate in mL/s and f_{CO2} is the CO_2 to fuel consumption rate in grams per millilitre (kg per litre) of fuel (g/mL or kg/L).

Other than instantaneous fuel consumption model, several models from SIDRA are also seen in estimating aggregate fuel consumption and emission (Bowyer et al. 1985). The generated emission data from SIDRA were then used to calibrate the proposed regression models to represent the relationship between vehicle emissions and traffic characteristics.

3.3. Case Study Parameters

The parameters for the case study are described here. The modelled arterial road has a speed limit v_{max} = 60 km/h, which is typical for urban roads in Malaysia (Road Transport Act 1987). Traffic is assumed to consist of 100% passenger cars that increase at the same rate for the given intersections. An unadjusted saturation flow rate is assumed at 1950 tcu/h (passenger car/hour/lane), and cycle length is 140 seconds for the signalised intersection. Three traffic signals are located at a distances L = 1.7 km from each other and operated under fixed time traffic control. Four seconds yellow time and two seconds all-red time are used between phases. Geometric characteristics and phase-control scheme for the three selected sites are shown in Figure 2. Traffic volume and cycle length are given in Table 1.

A series of scenarios were then created by varying the parameters: cycle time and demand. The inputs for traffic volume were set ranging from 0.1 to 4 to observe the breakpoints for the changes in emission at the respective three intersections. Simulation outputs describing delay, queue, degree of saturation and CO_2 emissions was obtained for each movement. To simplify the analysis process, we assumed ideal weather and pavement condition for all intersection analysis. The microsimulation model parameters, such as the queue gap distance, the mean target headway between a vehicle and car-following vehicle, etc., were not varied in this case study; default values were used. Although these parameters have a significant influence on traffic dynamics at intersections, it is assumed that they do not vary much within the case study network.

Figure 2: Geometric characteristics and signal phase of the selected sites

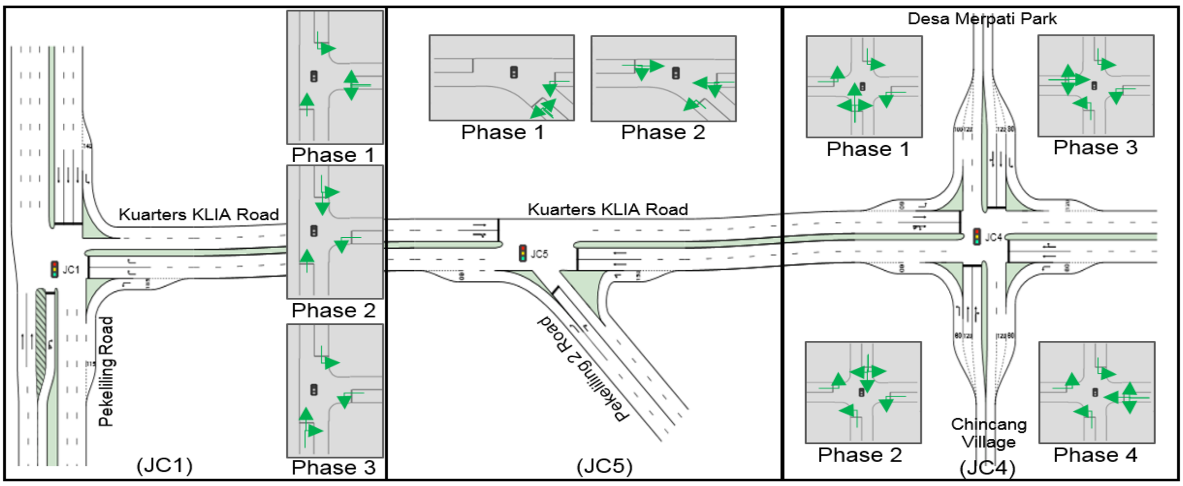


Table 1: Information for the selected signalised intersections

Intersection	Approaches	Traffic volume (pcu/h)				
		LT	T	RT	U	Total
Pekeliling Road (Route 27) – Kuarters KLIA Road (Route 344) (JC1)	Northbound	573	3422			3995
	Eastbound	1173		1643		2816
	Southbound		697	251	145	1093
Pekeliling Road 2 (Route 342) – Kuarters KLIA Road (Route 344) (JC5)	Westbound		1119	10		1129
	Eastbound	180	1745			1925
	Southeast bound	379		5		384
Kuarters KLIA Road (Route 344) – Desa Merpati Park (Route B4) – Chincang Village Kuarters KLIA Road (Route B4) (JC4)	Westbound	191	237	291	324	1043
	Northbound	104	175	837		1116
	Eastbound	49	409	73		531
	Southbound	629	335	9		973

3.4. Description of Study Sites

Figure 3: Aerial view of the study area (Google Map)

The case study site is a suburban arterial road that was constructed for the area surrounding Sepang International Circuit, an international race track located 60 km outside the centre of Malaysia's capital Kuala Lumpur, and located right beside Kuala Lumpur International Airport (KLIA). Figure 3 shows the aerial view of the studied area. The study area covers three signalised intersections along Kuarters Road (Route 344), which are categorised into Route 344 - Route 27 (JC1), Route 344 - Route 342 (JC5), and Route 344 - Route B48 (JC4). Route 27 connect vehicles from KLIA Extension highway to nearby cities, i.e. Nilai, Salak Tinggi and Sepang. Most of the approaching roads of Intersection JC1 and JC4 have exclusive turning bays. Also to be noted is that, data collection at these intersections have been gathered for 13 hours in conjunction with Grand Prix racing event held at the international circuit, under a state of oversaturated traffic condition.

Intersection JC1 is a congested crossing with three arms. The north arriving direction has four lanes, one for left-turn, and three for driving through the intersection. The south arriving direction has three lanes, but here two lanes are for continuous through, and one is for right and U-turn. The west arriving direction also has three lanes, where two lanes are for right-turn and one for left-turn. About 1.7 km east of the first intersection described above is the second intersection, JC5, a three arm signalised intersection. Here, the west arm consisting of traffic from the first intersection, has two lanes, one for straight through the intersection and one for right and straight through. The east arm has three lanes, two for straight through the intersection and one for left-turn. The south-east arriving direction has two lanes, one for a left turn and one for a right turn. Another 1.7 km east of the second intersection is the third intersection, JC4, a four arm signalised intersection. All the four arriving directions have three lanes, one for left-turn, one for straight through the intersection, and one for right and straight through. The turning movements for each intersection are displayed in Figure 2.

4. Results

The results presented in the next two sub sections are to quantify the influence of traffic flows on air pollutant emission and the influence of degree of saturation on air pollutant emission. The emissions are reported based on kilogrammes per hour.

4.1. Influence of traffic flows on air pollutant emission

Figure 4, 5 and 6 illustrates the amount of CO_2 emission predicted by SIDRA for a single movement at intersection JC1, JC5, and JC4 respectively. For intersection JC1, emissions were constant up to flow of approximately 1800 kg/h (flow = 2269 veh/h), at which point emissions began to increase. As shown in the figures, it is clear that two different linear relationships between flows and degree of saturation, respectively with emissions can be observed. Critical points where a significant difference in emission slope can also be seen to separate undersaturated and oversaturated traffic condition. This is the point where piecewise linear regression model with two linear slopes, an intercept, and a breakpoint were used to represent CO_2 emission rate against traffic flow. The intercept is the CO_2 emission rate at the point traffic flow = 0. The breakpoint represents the point at which the CO_2 emission rate changes between that found at under-saturated traffic state, where CO_2 is at a less steep gradient, and that found at over-saturated traffic state, where CO_2 begins to increase more rapidly with traffic flow. With this breakpoint, we initially presume this point as the start of oversaturation, which will be verified in the subsequent sub-sections. The CO_2 emissions are hence, given by the following set of piecewise linear equations:

For intersection JC1,

$$CO_2 = 0.805\,(\text{Flow}) - 33 \qquad \text{for } Q \leq 2269 \qquad \text{(Equation 7)}$$
$$CO_2 = 1.897\,(\text{Flow}) - 2511 \qquad \text{for } Q > 2269$$

For intersection JC5,

$$CO_2 = 0.234\,(\text{Flow}) - 4 \qquad \text{for } Q \leq 1737 \qquad \text{(Equation 8)}$$
$$CO_2 = 1.516\,(\text{Flow}) - 2231 \qquad \text{for } Q > 1737$$

For intersection JC4,

$$CO_2 = 0.42\,(\text{Flow}) - 4.184 \qquad \text{for } Q \leq 373 \qquad \text{(Equation 9)}$$
$$CO_2 = 4.078\,(\text{Flow}) - 1369 \qquad \text{for } Q > 373$$

A sudden rise in emission at the intersection is probably due to some vehicles from across the lanes must stop at the red signal, while, others are manoeuvring. Various driving events like idling, accelerating, decelerating, and cruising are commonly seen at signalised intersection, and the alternating combination of driving modes produce variable air-to-fuel requirements, which affect the emissions of pollutants differently. The significant increases in emissions at JC1 for example, can also be explained by the delays and queues observed in Figure 7 when traffic approaching oversaturated state.

Figure 4: Geometric characteristics and signal phase for intersection JC1

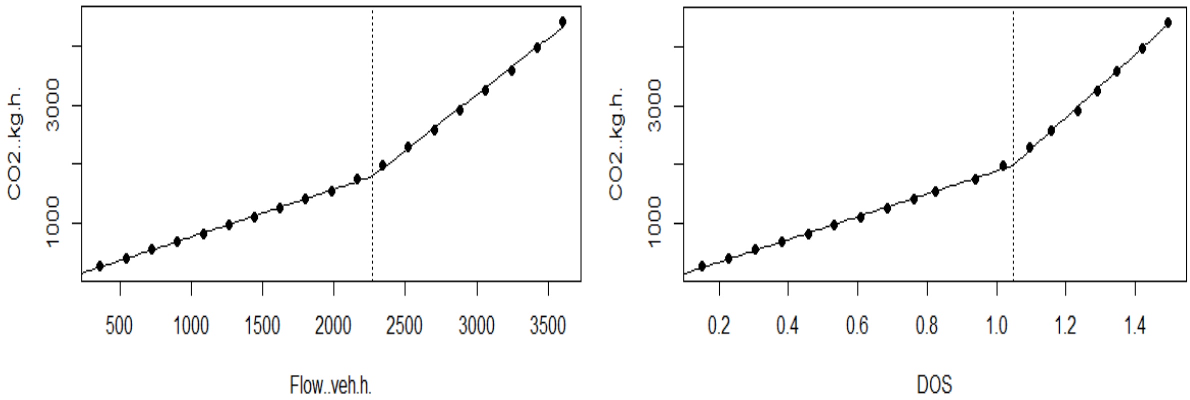


Figure 5: Geometric characteristics and signal phase for intersection JC5

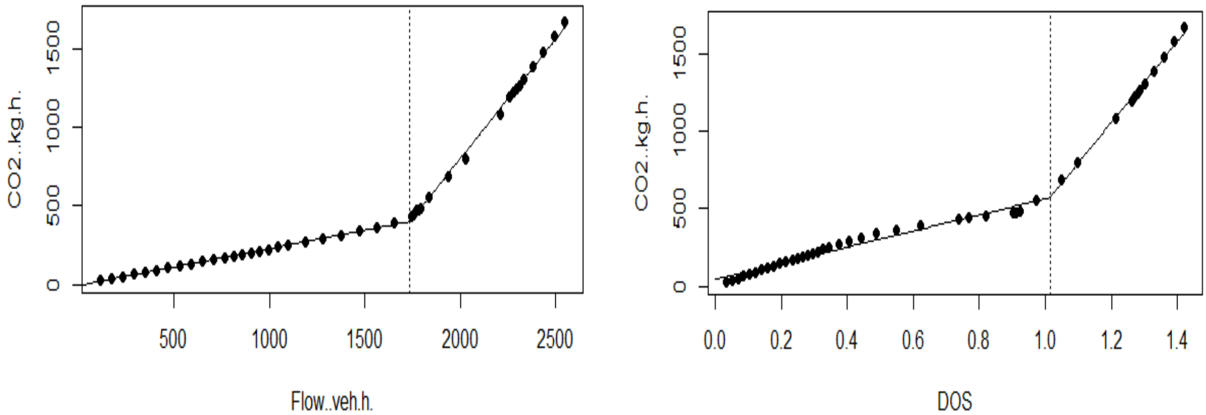


Figure 6: Geometric characteristics and signal phase for intersection JC4

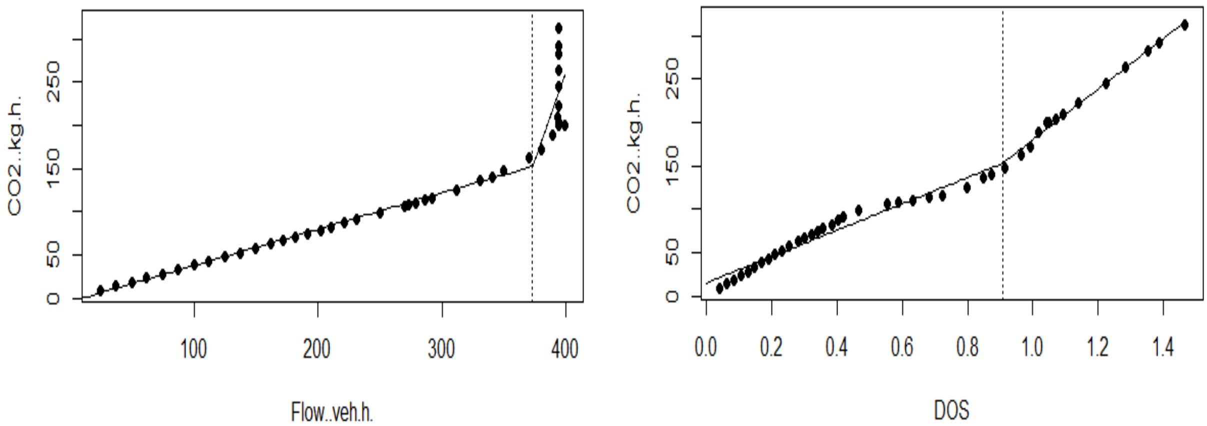
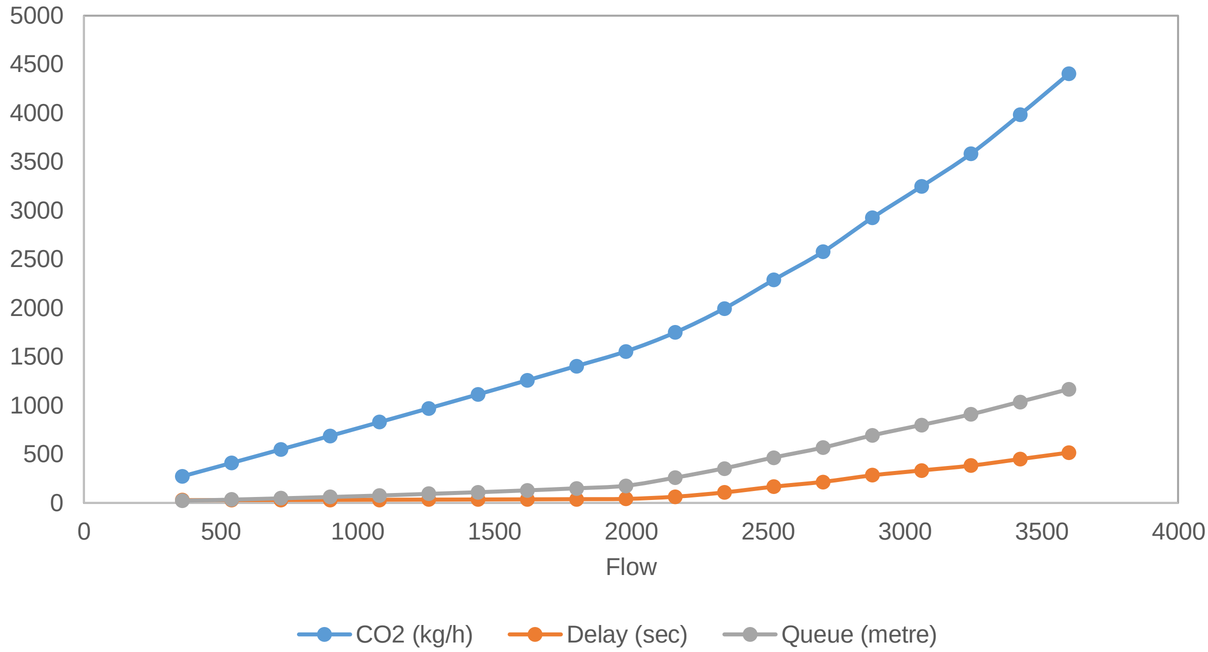


Figure 7: Comparing CO_2 emission, delay and queue for intersection JC1



4.2. Influence of degree of saturation on air pollutant emission

The amount of CO_2 emission exhibited different relationship at a different degree of saturation. A plot of CO_2 emission against the degree of saturation is provided in Figure 4, 5 and 6 for the same volume ratio. These plots showed similar trends as the previous plot with respect to traffic flow. As traffic demand increases (reflected in v/c ratio), the pollutant average emission rates increase for the three intersections. However, there is a high jump in emission rates as demand exceeds capacity (v/c>1) when the intersection shifts to oversaturation state, hence verifying our initial presumption. We also applied piecewise regressions using R package Segmented (Muggeo, 2008) to find the breakpoint of the relationship between the degree of saturation and emission. These results are consistent with some previous studies (Hellinga et al. 2000; Salamati et al. 2015), which have shown a strong linear relationship between CO_2 and degree of saturation. The CO_2 emissions are henceforth, given by the following set of piecewise linear equations:

For intersection JC1,

$$CO_2 = 1938.2\,(DOS) - 47.3 \qquad \text{for } v/c \leq 1.047 \qquad \text{(Equation 10)}$$
$$CO_2 = 5362.9\,(DOS) - 1.047 \qquad \text{for } v/c > 1.047$$

For intersection JC5,

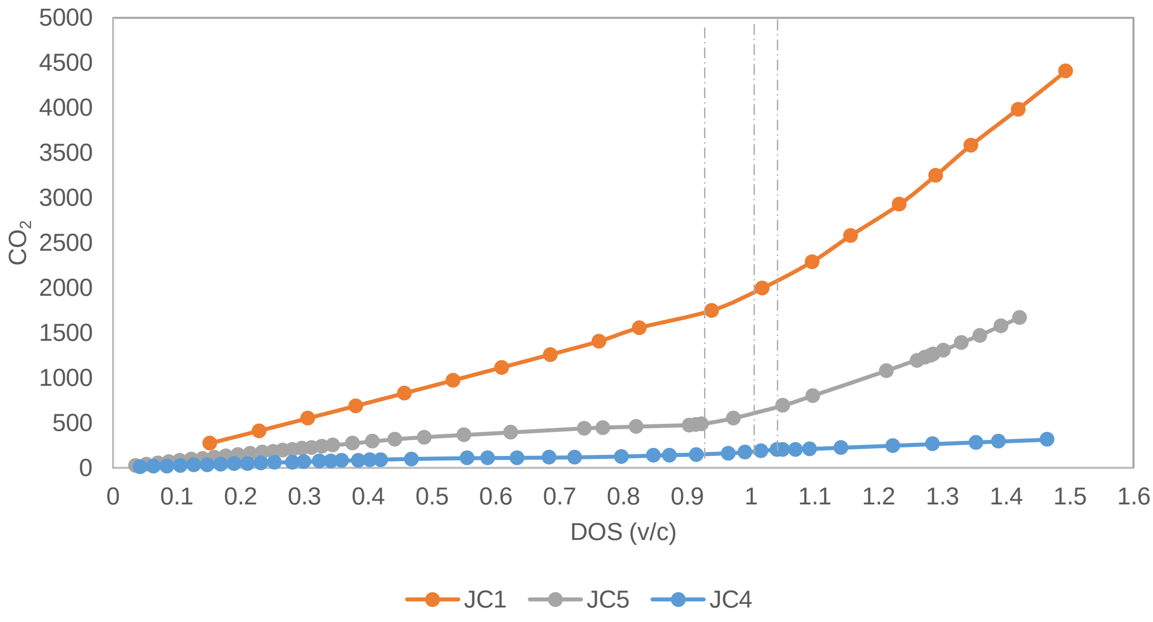
$$CO_2 = 519.07\,(DOS) + 46.17 \qquad \text{for } v/c \leq 1.015 \qquad \text{(Equation 11)}$$
$$CO_2 = 2604.6\,(DOS) - 2071.4 \qquad \text{for } v/c > 1.015$$

For intersection JC4,

$$CO_2 = 151.63\,(DOS) + 15.29 \qquad \text{for } v/c \leq 0.908 \qquad \text{(Equation 12)}$$
$$CO_2 = 291.87\,(DOS) - 112.1 \qquad \text{for } v/c > 0.908$$

However, these models have some weaknesses that compromise the interpretation of results. In particular, in Figure 8, the slopes corresponding to the segmented relationship are not (or marginally) significant in all scenarios. It appears that the uneven traffic volume at different intersections complicates the accurate estimation of degree of saturation. Moreover, the estimated slopes are intuitive and statistically significant. Figure 8 graphically presents the results for the three intersections, with regard to the observed and fitted emission against DOS.

Figure 8: Comparing different DOS breakpoints for intersection JC1, JC5, and JC4



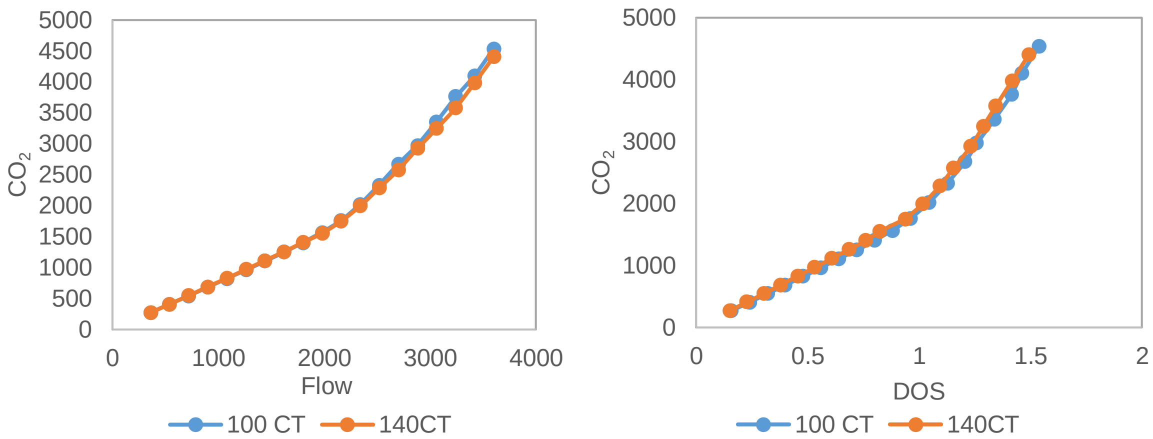
As observed in JC1 with the highest initial flow, the threshold that separated significant change in emission corresponds to a v/c value equal to 1.047. From this threshold onwards, their assessment of emission increases more rapidly. At JC5, the medium initial flow suggests that the threshold is situated at the value of 1.015 on the v/c scale. A steeper slope is then observed. On the other hand, the low initial flow scenario at JC4 suggests that the threshold is situated at the value of 0.908 on the v/c scale followed by a steeper slope. Overall, it appears that for v/c values of less than around 0.99, emissions of slower increment is seen. On the contrary, for v/c values higher than 0.99, emission will increase more drastically, hence suggesting the oversaturated point for the degree of saturation.

5. Discussion

Based on the results as discussed, traffic flows and degree of saturation are found to affect the amount of emission at a given intersection along signalised arterial. The methodology described is applied to demonstrate how comparisons can be made to determine the degree of saturation for oversaturated traffic state at signalised intersections with different demand levels. According to the Highway Capacity Manual (Transportation Research Board 2010), the degree of saturation for oversaturated conditions is suggested to be at 0.90. However, it is found that traffic flows and emission do affect the measure of effectiveness for the degree of saturation.

Traffic flow and degree of saturation both strongly influenced the distribution of CO_2 emission on the three intersections. A positive correlation with these variables was found for CO_2 emission. The piecewise regression identified a breakpoint at 2269 veh/h/approach, 1737 veh/h/approach, and 373 veh/h/approach respectively for traffic flows of JC1, JC5, and JC4 with their respective threshold of degree of saturation at 1.05, 1.02, and 0.91. It is clearly shown that relationship between emission and traffic flow fitted piecewise regression model with the highest R^2= 0.999 for JC1 and JC5, followed by 0.9258 for JC4. The relationship between the degree of saturation and emission also fitted piecewise linear regression with the highest R^2= 0.9975 for JC5, followed by 0.994 for JC1, and 0.9928 for JC4. Thus, our research results show that piecewise regression model provides a good estimate for trend pattern in emission at signalised intersection which forms an important tool to detrend the emission.

Figure 9: Effects of different cycle lengths (100 and 140 seconds) on emission



As shown in Figure 9, it also appears that emissions are insensitive to cycle time at signalised intersections when we tested cycle times for 100 seconds and 140 seconds. To our best knowledge, research related to the threshold of DOS does not pay attention to the transition between undersaturated and oversaturated traffic state, nor to the significance change in the emission and traffic flow. This kind of analysis, presented in Figure 4, 5, and 6, reveals interesting relations between breakpoints and variables of the traffic characteristics. The present study does not suggest any new theories, it only highlights new possibilities for analysing the degree of saturation. If the similar analysis is routinely carried out by researchers, the results may possibly lead to better insight into the mechanism behind the measure of effectiveness.

From the results presented above, it might be meaningful to reconsider the way oversaturated traffic are redefined by taking into account the differences in slope on the emissions. In particular, on the basis of the results of this research, a different approach to the degree of saturation is proposed according to the emission trend, whereby the point of saturation is proposed for v/c values at 0.99. The value of 0.99 is taken as the average of v/c values corresponding to the breakpoint for all volume types, indicating that for all volumes, the change in emission occurs around this value.

CO_2 emissions vary considerably and depend on the traffic flows with its associated degree of saturation. CO_2 emission increases with traffic flow. More specifically, higher CO_2 emissions were found under high traffic flow with a high degree of saturation. For oversaturation periods (v/c>1), signalised intersection show a large jump in the amount of emissions produced as demand exceeds capacity. The breakpoints are assumed to represent a transition between degrees of saturation for the change in emission. Until now, they were not utilised in interpreting their values by the graphical method. The present study shows that the breakpoint values estimated by piecewise linear regression, open new prospect in the interpretation of degree of saturation as a measure of effectiveness.

The strength of the methodology is in its simplicity and use of real-world emission profiles. This method is readily implemented in a simple spreadsheet tool to conduct these calculations in a planning-level at signalised intersections. To further improve the efficiency of the piecewise regression in this work, the following limitations can be considered for refinement. As the piecewise regression method can only partition a single input variable, one potential improvement is to generalise the method so as to allow segmentation of multiple variables in capturing the non-linearity in datasets. Further work is also needed to address the limitations such as particular signalised geometry, effects of other traffic characteristics (cycle time, green time) and validate them with field study.

6. Conclusion

This paper presented an analytical approach for modelling the impacts of traffic characteristics to the emission. In particular, the evaluation of traffic flows and degree of saturation and their impacts on air pollutant emission were evaluated and presented for a series of signalised arterial intersection in Kuala Lumpur. The results presented in this research provide some new insights on the relationship between degree of saturation and emissions. The major results of this study show that traffic flows and degree of saturation significantly affect the pollutant emissions, but the emissions are insensitive to cycle lengths at signalised intersections. Using a micro-analytical approach with adjustments for traffic volumes, CO_2 emissions were piecewise linearly or linearly related to the volume and their respective degree of saturation.

This study examine the impact of traffic volume and degree of saturation with respect to emission using piecewise linear relationship, and our approach and findings are not only relevant to emission estimation, but to other areas such as exposure, health risk evaluations and epidemiological studies. The approach presented herein links variables that are routinely available in the capacity analysis (entry and conflicting flows along with gap acceptance parameters) with predictions of emissions. As such, it can be considered as an extension of existing emission model to assess environmental impacts. The proposed methodology can also be viewed as a decision support tool for decision makers in the following areas: quantification of the environmental consequences of the installation of signalised intersection; comparison of the emissions between several intersection systems (roundabouts, unsignalised and signalised); selection of the geometric parameters of signalised intersections in order to achieve balance in predefined objectives concerning traffic calming without unduly causing excessive delay for drivers, while at the same time minimise the deleterious effect of the stops on pollutant emissions. Of course, further extensions of the approach to other vehicle types (emission results cannot be generalised without exploring other classes of vehicles – size, age, mileage and fuel type), and to multilane conditions signalised conditions needed to be completed prior to any large scale implementation.

While this study provides insight into the effects of various traffic parameters and CO_2 emissions in traffic context, further study is needed to provide a better framework for understanding and modelling the complex relationships associated with CO_2 emissions from vehicles. It is also important to examine a wider range of vehicles to better understand how these relationships change for another vehicle fleet. It may also be important to better understand the relative impact of driving behaviours on CO_2 emissions. Some more detailed microscopic parameters may also be worthwhile, to further investigate any relationships found. Additional research on developing emission models for CO_2 that incorporate driving behaviour is planned in conjunction with this study. First, the CO_2 emissions and driving parameters will be derived from the properties found in existing microscopic model as a secondary data, which is later integrated into macroscopic models. Additionally, parameters set for the Malaysian emission parameters will be estimated for each vehicle as well as for composite vehicles.

Acknowledgements

This research has been made possible through financial contributions from the Ministry of Education Malaysia (MOHE) under Fundamental Research Grant Scheme (FRGS) [Project code FRGS/2/2014/TK05/MUSM/03/1]. The authors would like to acknowledge MDS Consultancy Group for providing traffic data and also Mr. Chris Hough and Mr. Omar A. Mahsen, for their helpful discussions concerning their current project. The authors are also grateful to Miss Kueh Ling Lee from L&P Associates and Dr. Rahmi Ahcelik from Sidra Solutions, for their kind assistance in the computational efforts.

References

Afotey, B, Sattler, M, Mattingly, SP & Chen, VC 2013, 'Statistical model for estimating carbon dioxide emissions from a light-duty gasoline vehicle', *Journal of Environmental Protection*, vol. 4, no. 8A1, p. 8.

Akçelik, R, Smit, R & Besley, M 2012, 'Calibrating fuel consumption and emission models for modern vehicles,' *IPENZ transportation group conference, Rotorua, New Zealand*, 1-14.

Anderson, W, Kanaroglou, P, Miller, E & Buliung, R 1996, 'Simulating automobile emissions in an integrated urban model', *Transportation Research Record: Journal of the Transportation Research Board*,no. 1520, pp. 71-80.

Barth, M & Boriboonsomsin, K 2008, 'Real-world carbon dioxide impacts of traffic congestion', *Transportation Research Record: Journal of the Transportation Research Board*,no. 2058, pp. 163-171.

Biggs, D & Akcelik, R 1986, 'Energy-related model of instantaneous fuel consumption', *Traffic Engineering and Control*, vol. 27, no. 6, pp. 320-325.

Bowyer, DP, Akçelik, R & Biggs, D 1985, *Guide to fuel consumption analyses for urban traffic management*.

Cappiello, A, Chabini, I, Nam, EK, Lue, A & Zeid, MA 2002, 'A statistical model of vehicle emissions and fuel consumption,' *Intelligent Transportation Systems, 2002. Proceedings. The IEEE 5th International Conference on*, 801-809.

Coelho, MC, Farias, TL & Rouphail, NM 2009, 'A numerical tool for estimating pollutant emissions and vehicles performance in traffic interruptions on urban corridors', *International Journal of Sustainable Transportation*, vol. 3, no. 4, pp. 246-262.

Crawley, MJ 2012, John Wiley & Sons, Imperial College London at Silwood Park, UK.

De Coensel, B, Botteldooren, D, Vanhove, F & Logghe, S 2007, 'Microsimulation based corrections on the road traffic noise emission near intersections', *Acta acustica united with acustica*, vol. 93, no. 2, pp. 241-252.

De Vlieger, I, De Keukeleere, D & Kretzschmar, J 2000, 'Environmental effects of driving behaviour and congestion related to passenger cars', *Atmospheric Environment*, vol. 34, no. 27, pp. 4649-4655.

EPA 2003, *User's Guide to MOBILE 6.1 and MOBILE 6.2.*, viewed 20 September 2016, <https://www3.epa.gov/otaq/models/mobile6/420r03010.pdf>.

EPA 2009, *MOVES 2010 Policy Guidance*, viewed 20 June 2016, <https://www3.epa.gov/otaq/models/moves/420b09046.pdf>.

Frey, H, Rouphail, N, Unal, A & Colyar, J 2001, 'Emissions reduction through better traffic management: An empirical evaluation based upon on-road measurements', 369 p.

Ge, Y-E, Prentkovskis, O, Tang, C, Saleh, W, GH Bell, M & Junevičius, R 2015, 'Solving Traffic Congestion from the Demand Side', *PROMET-Traffic&Transportation*, vol. 27, no. 6, pp. 529-538.

Hellinga, B, Khan, MA & Fu, L 2000, 'Analytical Emission Models for Signalised Arterials', vol. #, no. #, p. #.

Huai, T, Durbin, TD, Younglove, T, Scora, G, Barth, M & Norbeck, JM 2005, 'Vehicle specific power approach to estimating on-road NH3 emissions from light-duty vehicles', *Environmental science & technology*, vol. 39, no. 24, pp. 9595-9600.

International Energy Agency 2015, *CO2 Emissions from Fuel Combustion,* 2015 edn., France.

International Energy Agency (IEA) 2015, Internation Energy Agency, Paris, France.

Joumard, R, André, M, Vidon, R, Tassel, P & Pruvost, C 2000, 'Influence of driving cycles on unit emissions from passenger cars', *Atmospheric Environment*, vol. 34, no. 27, //, pp. 4621-4628.

Lv, J 2012, *Signal Timing Optimization to Improve Air Quality*, thesis, Texas A&M University.

Ministry of Transport 2015, *Annual Report of Road Transport Statistics Malaysia (2014),*

Muggeo, VM 2003, 'Estimating regression models with unknown break‐points', *Statistics in medicine*, vol. 22, no. 19, pp. 3055-3071.

Muggeo, VM 2008, 'Segmented: an R package to fit regression models with broken-line relationships', *R news*, vol. 8, no. 1, pp. 20-25.
Nielsen 2014, *Rising Middle Class will Drive Global Automotive Demand in the Coming Two Years*, viewed 23 August 2016, <http://www.nielsen.com/my/en/press-room/2014/rising-middle-class-will-drive-global-automotive-demand.html>.
R Core Team 2014, *R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. 2013,* ISBN 3-900051-07-0.
Road Transport Act 1987, *Laws of Malaysia*, Malaysia.
Salamati, K, Rouphail, NM, Frey, HC, Liu, B & Schroeder, BJ 2015, 'Simplified Method for Comparing Emissions in Roundabouts and at Signalized Intersections', *Transportation Research Record: Journal of the Transportation Research Board*,no. 2517, pp. 48-60.
Scora, G & Barth, M 2006, *Comprehensive Modal Emission Model (CMEM), Version 3.01 User's Guide.* , University of California, California.
Sjodin, A, Persson, K, Andreasson, K, Arlander, B & Galle, B 1998, 'On-road emission factors derived from measurements in a traffic tunnel', *International journal of vehicle design*, vol. 20, no. 1-4, pp. 147-158.
Slezakova, K, Castro, D, Delerue–Matos, C, da Conceição Alvim–Ferraz, M, Morais, S & do Carmo Pereira, M 2013, 'Impact of vehicular traffic emissions on particulate-bound PAHs: levels and associated health risks', *Atmospheric Research*, vol. 127, pp. 141-147.
Smit, R 2006, *An examination of congestion in road traffic emission models and their application to urban road networks*, thesis, Griffith University.
The World Bank 2015, *Population*, viewed 22 August 2016, <http://data.worldbank.org/indicator/SP.POP.TOTL?locations=MY>.
Transportation Research Board 2010, *Highway Capacity Manual*, Washington, DC, USA.
Zhang, K & Batterman, S 2010, 'Near-road air pollutant concentrations of CO and PM2.5: A comparison of MOBILE6.2/CALINE4 and generalized additive models', *Atmospheric Environment*, vol. 44, no. 14, 5//, pp. 1740-1748.
Zhang, K & Batterman, S 2013, 'Air pollution and health risks due to vehicle traffic', *Science of the total Environment*, vol. 450, pp. 307-316.
Zhang, K, Batterman, S & Dion, F 2011, 'Vehicle emissions in congestion: Comparison of work zone, rush hour and free-flow conditions', *Atmospheric Environment*, vol. 45, no. 11, 4//, pp. 1929-1939.
Zheng, X & Zhang, L 2015, 'Ecodriving for Reduction of Bus Transit Emission with Vehicle's Hybrid Dynamic Model', *Mathematical Problems in Engineering*, vol. 2015, pp. 1-8.

Appendices

```
#Load file

read.delim(file.choose(),header=T)

attach(book1)

names(book1)

#Plot data

plot(Flow..veh.h.,Delay..sec.,main="JC1")

#To get estimated breakpoint

lin.mod = lm(CO2..kg.h.~Flow..veh.h.)

segmented.mod = segmented(lin.mod, seg.Z = ~Flow..veh.h., psi=2000)

plot(Flow..veh.h.,CO2..kg.h., pch=16, ylim=c(200,4500))

slope(segmented.mod)

summary(segmented.mod)
```

```
piecewise2 <- lm(CO2..kg.h. ~ Flow..veh.h.*(Flow..veh.h. < 2269.889) +
Flow..veh.h.*(Flow..veh.h. > 2269.889))

summary(piecewise2)

#To plot piecewise linear equation

curve((-2511 + 2478) + (1.897-1.092)*x, add=T, from=0, to=2269.889)

curve(-2511 + 1.897*x, add=T, from=2269.889, to=max(Flow..veh.h.))

abline(v=2269.889, lty=3)

#Test for a change in slope

davies.test(lin.mod,~Flow..veh.h.)

oseg=segmented(lin.mod,seg.Z = ~Flow..veh.h.,psi=2000)

slope(oseg)
```