# Recalibration of a Vehicle Power Model for Fuel and Emission Estimation and its Effect on Assessment of Alternative Intersection Treatments

## Rahmi Akçelik, Robin Smit and Mark Besley

**Rahmi Akçelik**: Corresponding author
Director, Akcelik & Associates Pty Ltd
Email: rahmi.akcelik@sidrasolutions.com
Phone: +61 3 9857 4943, Fax: +61 3 9857 7462
Mail: P O Box 1075 G, Greythorn Vic 3104, Australia
Website: www.sidrasolutions.com

**Robin Smit**
Hon. Senior Research Fellow, University of Queensland,
Centre for Transport Strategy, School of Civil Engineering
Email: robin.smit@yahoo.com.au

**Mark Besley**
Director, Akcelik & Associates Pty Ltd
Email: mark.besley@sidrasolutions.com

Submission date: 24 April 2014

Word count: Approximately 7400 words including 6 figures and 3 tables (max 7500 words)

**Paper presented at the 4th International Roundabout Conference,
Transportation Research Board, Seattle, WA, USA, 16-18 April 2014**

## ABSTRACT

Estimation of fuel consumption and pollutant emissions for evaluating road traffic conditions is useful for environmental assessment in traffic design, operations and planning. This also forms the basis of operating cost modeling. Fuel consumption and emission ($CO_2$, CO, HC, $NO_x$) models with four levels of aggregation for traffic engineering and transport planning purposes were developed by the first author and his colleagues at the Australian Road Research Board in the 1980s. These models are based on vehicle power requirements, and the four-mode elemental (modal) and the more detailed instantaneous forms of the model are implemented in the SIDRA INTERSECTION and SIDRA TRIP software packages.

This paper describes the recent work on recalibration of light and heavy vehicle parameters used by this model using a large empirical database for a modern vehicle fleet. Implications of the change in fuel and emission model parameters on intersection assessment are considered. A roundabout evaluation case is presented assessing the effectiveness of roundabout metering signals using the fuel consumption and emission models with (i) older vehicle parameter values and (ii) the recalibrated parameter values to investigate whether the changes in vehicle parameters change the results significantly. The model provided in the SIDRA INTERSECTION software package is used for this purpose.

## INTRODUCTION

Environmental assessment in traffic design, operations and planning can be conducted using models to estimate fuel consumption and pollutant emissions as a function of traffic conditions. This also forms the basis of operating cost modeling.

Fuel consumption and emission ($CO_2$, CO, HC, $NO_x$) models with four levels of aggregation for traffic engineering and transport planning purposes were developed by the first author and his colleagues based on extensive research at the Australian Road Research Board in the 1980s *(1-19)*. These models are based on vehicle power requirements, and the four-mode elemental (modal) and the more detailed instantaneous forms of the model are implemented in the SIDRA INTERSECTION and SIDRA TRIP software packages *(20-23)*.

Studies of fuel consumption and emission using SIDRA software were reported in the past *(24, 26)*. In more recent years, an application of the model to investigate of fuel consumption, pollutant emission and operating cost savings at a roundabout with metering signals was reported by the first author *(27)*.

This model provides highly accurate fuel consumption estimates for traffic analysis since there is no simplification of traffic information into such aggregate variables as average travel speed, average running speed and number of stops. However, it has been recognized that it is necessary to update the vehicle parameters used by the model, especially for emission estimates, in order to reflect more recent changes in vehicle characteristics (rated engine power, catalyst loading and composition, engine management system, etc.) and fleet composition *(28)*.

Research was undertaken recently to calibrate the light and heavy vehicle parameters used by the fuel consumption and emission models in SIDRA INTERSECTION and SIDRA TRIP based on a large empirical database for a modern vehicle fleet. The preliminary results of this effort were reported by the authors previously *(29)*.

The research involved the use of an empirical database (NISE 2) incorporating a large range of fuel consumption and emission data for about 400 vehicles representing a cross section of typical vehicles on Australian metropolitan roads *(30-32)*. Data were collected in a vehicle emissions test laboratory using a real-world driving cycle called CUEDC-P (composite urban emission drive cycle for petrol vehicles) developed from Australian driving pattern data collected in the field. This drive cycle consists of four phases representing *Residential*, *Arterial*, *Freeway* and *Congested* driving conditions.

This paper describes the instantaneous form of the fuel consumption and $CO_2$ models, presents the model recalibration results for a number of vehicles, and compares the default vehicle parameters for the composite "Light Vehicle" in SIDRA INTERSECTION before and after recalibration.

Implications of the change in fuel and emission model parameters on intersection assessment are considered. A roundabout evaluation case is presented assessing the effectiveness of roundabout metering signals using fuel consumption and emissions ($CO_2$, HC, CO, $NO_x$) as well as operating costs (including vehicle operating cost and value of time) with (i) older vehicle parameter values and (ii) the recalibrated parameter values, to investigate whether changes in vehicle parameters change the results significantly. The model provided in the SIDRA INTERSECTION software package is used for this purpose.

## MODEL PARAMETERS

The fuel consumption and emission models use two groups of parameters, namely vehicle parameters, and traffic and road parameters.

Vehicle parameters include loaded mass, idle fuel or emission rates, and fuel or emission efficiency rates. The vehicle parameters used in the fuel consumption and emission models are derived considering fleet composition (percentage of vehicle kilometres for each vehicle type) with more detailed vehicle data including fuel type (% diesel), maximum engine power, power to weight ratio, number of wheels and tyre diameter, rolling resistance factor, frontal area and the aerodynamic drag coefficient.

In SIDRA INTERSECTION, fuel consumption, emissions and cost are calculated for different *movement classes* including *Light Vehicles, Heavy Vehicles, Buses, Bicycles, Large Trucks, Light Rail / Trams* and two *user-defined classes*. Traditionally, a more aggregate "heavy vehicle" designation is used for traffic modeling as well as fuel and emission modeling, where a heavy vehicle is defined as any vehicle with more than two axles or with dual tyres on the rear axle. The US Highway Capacity Manual *(33)* defines a heavy vehicle as "a vehicle with more than four wheels touching the pavement during normal operation". Thus, buses, trucks, semi-trailers (articulated vehicles), cars towing trailers or caravans, tractors and other slow-moving vehicles are classified as heavy vehicles. All other vehicles are defined as light vehicles (cars, vans, small trucks).

Traffic and road parameters used directly in the SIDRA INTERSECTION model for fuel and emission estimation include speed, acceleration rate and grade parameters. A detailed description of the polynomial acceleration model used for this purpose is available *(16, 20)*.

SIDRA INTERSECTION uses a macroscopic four-mode elemental (modal) model. For each lane of traffic, the traffic model derives vehicle paths (drive cycles) consisting of a series of *cruise*, *acceleration*, *deceleration* and *idling (stopped) time* elements (*Figure 1*) for specific traffic conditions represented by intersection geometry, traffic control and demand flows based on data supplied by the user. Thus, the vehicle paths (drive cycles) generated by SIDRA INTERSECTION are very different for different intersection types (signalized, roundabout, sign-controlled), for different signal phasing arrangements, for different signal timings for a given phasing arrangement, for give-way (yield) and stop control (two-way or all-way), and for different congestion levels.

Vehicle paths (drive cycles) are derived and the fuel consumption and emission models are applied to queued (stopped) and unqueued (unstopped) vehicles belonging to different *movement classes* in each lane separately, and then the total values are calculated for all traffic using the lane.

Vehicle paths for *unqueued vehicles* are constructed taking into account (i) cruise on entry to the approach, (ii) slow-down to a safe negotiation speed or full stop on the approach, and (iii) negotiation of the intersection departure area at the safe negotiation speed.

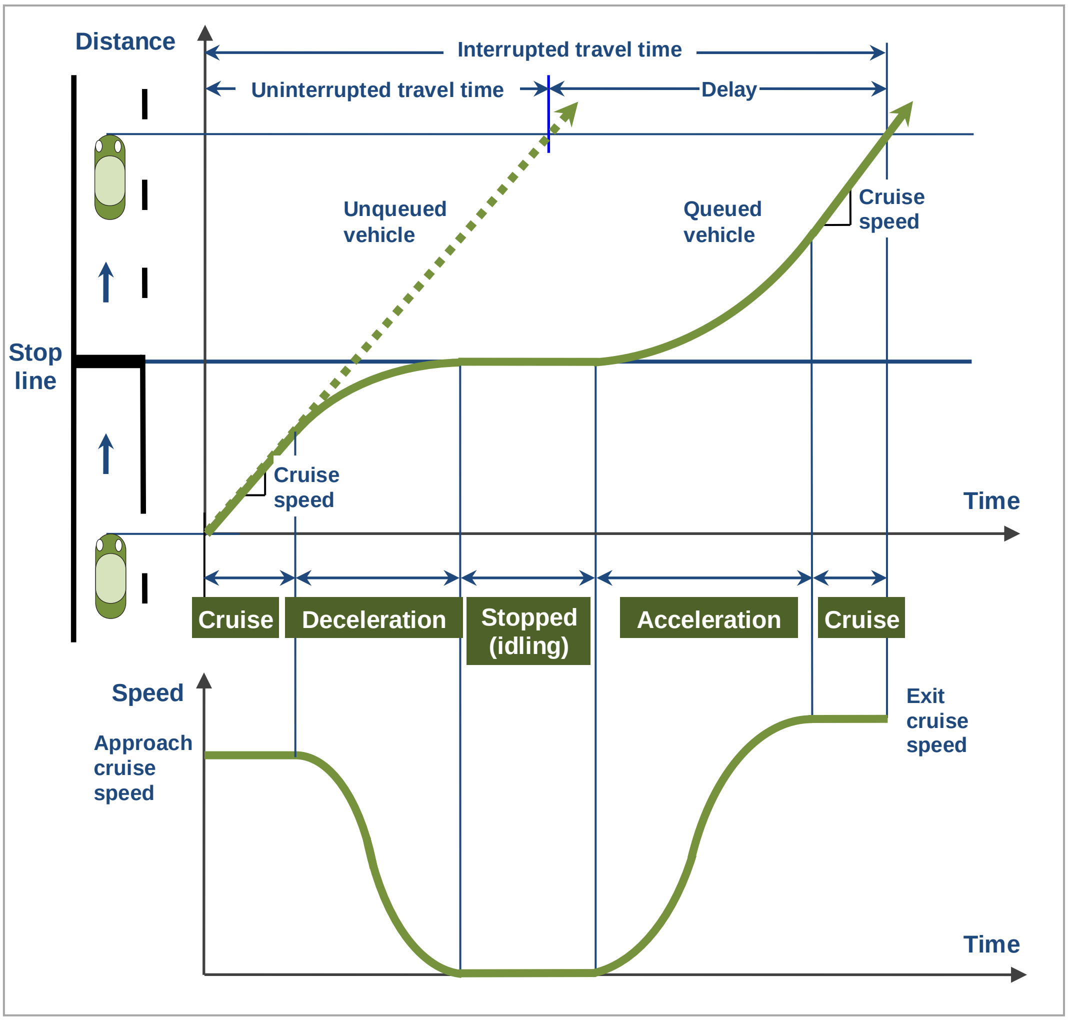

***Figure 1 - Vehicle path (drive cycle) during a stop - start manoeuvre (example)***

Vehicle paths for *queued vehicles* (*Figures 1 and 2*) are constructed taking into account (i) cruise on entry to the approach, (ii) major stop (stop or slow down from approach cruise speed), (iii) queue move-ups (repeated stops and starts in the queue) and (iv) negotiation of the intersection departure area at the safe negotiation speed. .

Once the vehicle travel paths are determined, the fuel consumption and emission values are calculated for each of the four driving elements (modes) for each vehicle path, the results are added together for the entire vehicle path, and aggregate values for lanes and origin-destination (turning) movements are determined according to flow proportions of queued and unqueued vehicles and movement classes.

Thus, the key to the estimation of fuel consumption and emissions is detailed modelling of stop-starts in addition to delays and queues. The stop-start model is strongly related to the modelling of back of queue and delay at all types of intersection. This is depicted in *Figure 2* where *queue move-ups* are seen to be related to *overflow queues*. Stop - start modeling is not included in the HCM for intersections *(33)*. In SIDRA INTERSECTION, a gap-acceptance model by signal analogy is used as a basis of modeling stop-starts for roundabouts and two-way sign control *(34, 35)*.

The instantaneous models of fuel consumption and $CO_2$ are described in the following section. Other emission models have the same structure as the fuel consumption model.

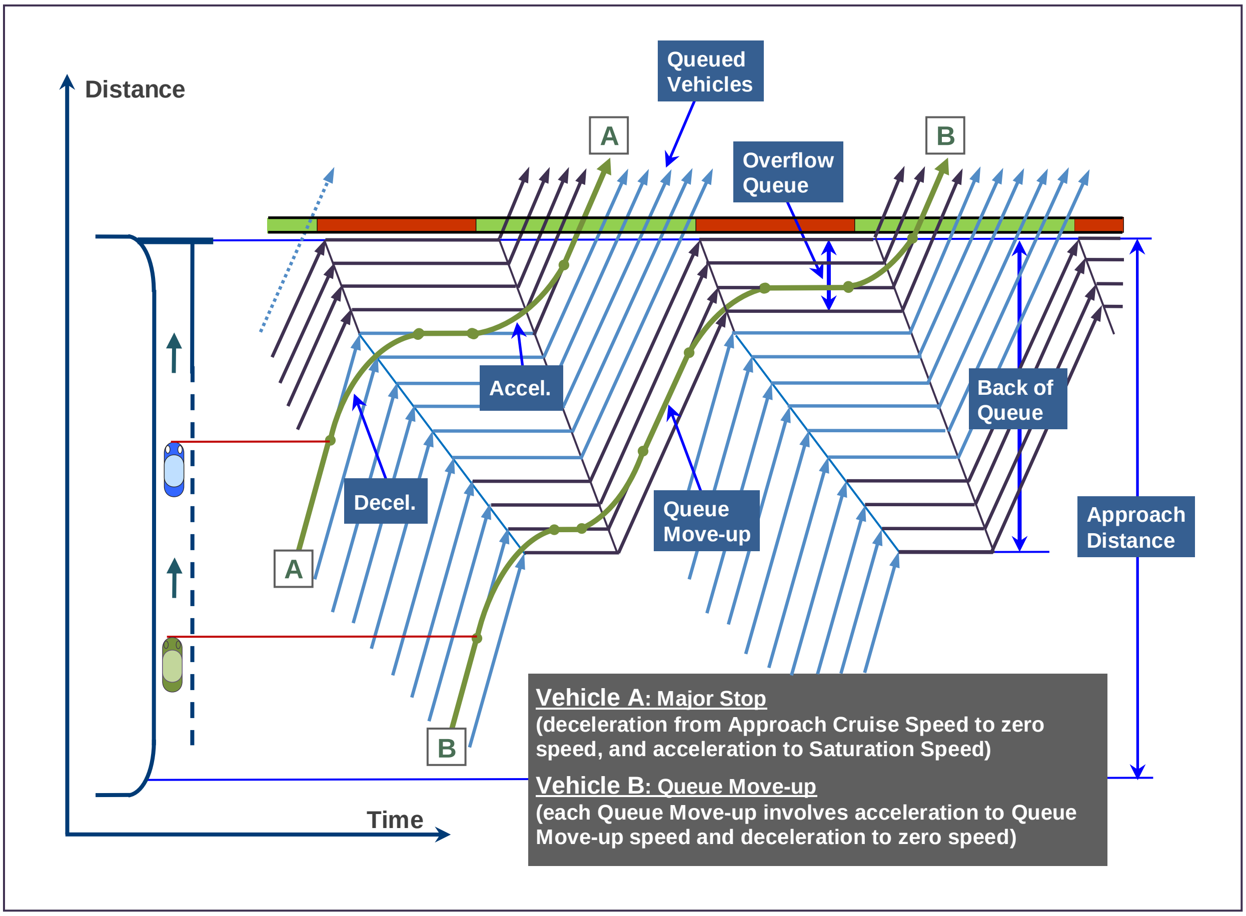

***Figure 2 - Relationship between queue move-ups (multiple stops) and back of queue***

## MODEL FOR FUEL CONSUMPTION AND CO$_2$

The original fuel consumption model developed in the 1980s can be expressed in terms of the energy, power or tractive force required by the vehicle. The instantaneous model estimates the fuel consumption rate (mL/s) as a value per unit time measured at any instant during the trip and expressed as a function of the tractive power required by the vehicle:

$$f_t = \alpha + \beta_1 P_T + [\beta_2 \, a \, P_I]_{a>0} \qquad \text{for } P_T > 0 \qquad (1)$$
$$= \alpha \qquad \text{for } P_T \le 0$$

$$P_T = \min\,(P_{max}, P_C + P_I + P_G) \qquad (2)$$

$$P_C = b_1 v + b_2 v^3 \qquad (3)$$

$$P_I = M_v \, a \, v / 1000 \qquad (4)$$

$$P_G = 9.81 \, M_v \, (G/100) \, v / 1000 \qquad (5)$$

$$\alpha = f_i / 3600 \qquad (6)$$

where

$f_t$ = instantaneous fuel consumption rate (mL/s),
$P_T$ = total tractive power (kilowatts, kW),
$P_{max}$ = maximum engine power (kW),
$P_C$ = *cruise* component of total power (kW),

$P_I$ = *inertia* component of total power (kW),

$P_G$ = *grade* component of total power (kW),

$G$ = road grade (per cent), negative if downhill,

$M_v$ = vehicle mass (kg) including occupants and any other load,

$v$ = instantaneous speed (m/s) = v (km/h) / 3.6

$a$ = instantaneous acceleration rate (m/s$^2$), negative for deceleration,

$\alpha$ = constant idle fuel consumption rate (mL/s), which applies during all modes of driving (as an estimate of fuel used to maintain engine operation),

$f_i$ = constant idle fuel consumption rate in mL/h,

$b_1$ = Drag fuel consumption parameter related mainly to the rolling resistance (kN),

$b_2$ = Drag fuel consumption parameter related mainly to the aerodynamic drag (kN/(m/s)$^2$),

$\beta_1$ = the efficiency parameter which relates fuel consumed to the total power provided by the engine, it can be shown to be fuel consumption per unit of energy (mL/kJ or g/kJ), and

$\beta_2$ = the efficiency parameter which relates fuel consumed during positive acceleration to the product of acceleration rate and inertia power when n = 1.0 (mL/(kJ.m/s$^2$) or g/(kJ.m/s$^2$)).

The instantaneous cruise fuel consumption rate ($a = 0$, $P_I = 0$) on a on a level road ($G = 0$, $P_G = 0$) is given by:

$$f_{ct} = \alpha + \beta_1 P_C \tag{7a}$$

$$f_{ct} = \alpha + \beta_1 (b_1 v + b_2 v^3) \tag{7b}$$

Parameters A and B specified as input for the software are calculated from:

$$A = 1000\, \beta_1 b_1 \tag{8a}$$

$$B = \beta_1 b_2 / 0.01296 \tag{8b}$$

where the parameter units are mL/km for A and (mL/km)/(km/h)$^2$ for B.

Parameters A and B ($b_1$ and $b_2$) provide a reasonable representation of drag (cruise) power to be provided by the engine so that the model application for fuel consumption is based on a realistic definition of $P_C$, $P_I$ and $P_T$. Parameters $b_1$ and $b_2$ also reflect some component of drag associated with the engine.

The following simpler model has been developed as part of the recalibration effort and introduced in SIDRA INTERSECTION Version 6. It was obtained as an alternative model by dropping the ($a\,P_I$) term of *Equation (1)*:

$$f_t = \alpha + \beta P_T \quad \text{for } P_T > 0 \tag{9}$$
$$\phantom{f_t} = \alpha \quad \text{for } P_T \le 0$$

where parameters are as in *Equation (1)*.

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

$$f_t(CO_2) = f_{CO2}\, f_t(fuel) \tag{10}$$

where

$f_t(fuel)$ = fuel consumption rate in mL/s and,

$f_{CO2}$ = $CO_2$ to Fuel Consumption Rate in grams per millilitre (kg per litre) of fuel (g/mL or kg/L).

The model for estimating the *instantaneous Carbon Monoxide (CO), Hydrocarbons (HC)* and *Nitrogen Oxides ($NO_x$) emission rates* (mg/s), representing the emission production rate at any instant during the trip determined as a value per unit time, has the same structure as the instantaneous fuel consumption model with different parameters.

The method used to calibrate the fuel consumption and emission models is explained in a previous paper by the authors *(29)*.

## MODEL CALIBRATION RESULTS

The calibration confirmed that new vehicles are significantly more efficient with substantially lower fuel consumption and emission ($CO_2$, CO, HC, $NO_x$) rates. This result is as expected due to technological improvements in the vehicle fleet since the 1980s.

A comparison of the fuel consumption and $CO_2$ default parameters used in SIDRA INTERSECTION for light vehicles before and after recalibration is presented in *Table 1*.

Calibration results for individual vehicles of different types are given in *Figure 3* (vehicle characteristics listed include fuel density, D).

Measured and estimated values of fuel consumption and emission rates for some of the individual test vehicles for the CUEDC-P drive cycle are summarized in *Table 2*.

***Table 1 - Comparison of default parameters for Light Vehicle fuel consumption and $CO_2$ models before and after recalibration***

| Parameter | Description | Units | Old Defaults | New Defaults | Difference |
|---|---|---|---|---|---|
| $f_i$ | Idle fuel consumption rate | mL/h | 1350 | 1200 | -11% |
| **A** | $A = 1000\ \beta_1\ b_1$ | mL/km | 21.0 | 16.0 | -24% |
| **B** | $B = \beta_1\ b_1 / 0.01296$ | (mL/km)/ (km/h)$^2$ | 0.00550 | 0.00400 | -27% |
| $b_1$ | Drag fuel consumption parameter, mainly related to rolling resistance | kN | 0.233333 | 0.160000 | -31% |
| $b_2$ | Drag fuel consumption parameter mainly related to aerodynamic drag | kN/(m/s)$^2$ | 0.000792 | 0.000518 | -35% |
| $\beta_1$ | Efficiency parameter | mL/kJ | 0.090 | 0.100 | * |
| $\beta_2$ | Energy-acceleration efficiency parameter | mL/(kJ.m/s$^2$) | 0.030 | - | - |
| $M_v$ | Average vehicle mass | kg | 1400 | 1600 | 14% |
| $P_{max}$ | Maximum power | kW | 85 | 120 | 41% |
| **PWR** | Power to Weight Ratio | kW / t | 60.7 | 75.0 | 24% |
| $f_{CO2}$ | $CO_2$ emission rate | g/mL | 2.500 | 2.350 | -6% |

* The higher value of the efficiency parameter, $\beta_1$ compensates for elimination of the second parameter, $\beta_2$.

**Toyota Corolla Ascent 2004**

| $M_v$ | $P_{max}$ | $f_{co2}$ | $D_{fuel}$ | Eng. Cap. | Auto / Man |
|---|---|---|---|---|---|
| kg | kW | g / mL | g / L | L | |
| 1250 | 100 | 2.350 | 738.7 | 1.8 | Auto |

| $f_i$ | A | B | $b_1$ | $b_2$ | $\beta$ |
|---|---|---|---|---|---|
| mL/h | mL/km | mL/km/(km/h)$^2$ | kN | kN/(m/s)$^2$ | mL/kJ |
| 891 | 9.60 | 0.00373 | 0.0948 | 0.000478 | 0.1012 |

**Holden Commodore 2006**

| $M_v$ | $P_{max}$ | $f_{co2}$ | $D_{fuel}$ | Eng. Cap. | Auto / Man |
|---|---|---|---|---|---|
| kg | kW | g / mL | g / L | L | |
| 1810 | 131 | 2.350 | 738.7 | 3.6 | Auto |

| $f_i$ | A | B | $b_1$ | $b_2$ | $\beta$ |
|---|---|---|---|---|---|
| mL/h | mL/km | mL/km/(km/h)$^2$ | kN | kN/(m/s)$^2$ | mL/kJ |
| 1504 | 19.39 | 0.00406 | 0.1779 | 0.000483 | 0.1090 |

**Ford Territory 2004**

| $M_v$ | $P_{max}$ | $f_{co2}$ | $D_{fuel}$ | Eng. Cap. | Auto / Man |
|---|---|---|---|---|---|
| kg | kW | g / mL | g / L | L | |
| 2150 | 142 | 2.350 | 738.7 | 4 | Auto |

| $f_i$ | A | B | $b_1$ | $b_2$ | $\beta$ |
|---|---|---|---|---|---|
| mL/h | mL/km | mL/km/(km/h)$^2$ | kN | kN/(m/s)$^2$ | mL/kJ |
| 1479 | 24.32 | 0.00375 | 0.2484 | 0.000497 | 0.0979 |

**Isuzu FVR900 (T) 2005 (Diesel)**

| $M_v$ | $P_{max}$ | $f_{co2}$ | $D_{fuel}$ | Eng. Cap. | Auto / Man |
|---|---|---|---|---|---|
| kg | kW | g / mL | g / L | L | |
| 12080 | 164 | 2.633 | 830.0 | 7.8 | Manual |

| $f_i$ | A | B | $b_1$ | $b_2$ | $\beta$ |
|---|---|---|---|---|---|
| mL/h | mL/km | mL/km/(km/h)$^2$ | kN | kN/(m/s)$^2$ | mL/kJ |
| 2274 | 201.31 | 0.00818 | 2.7207 | 0.001432 | 0.0740 |

**Hino RB8 2006 (Diesel)**

| $M_v$ | $P_{max}$ | $f_{co2}$ | $D_{fuel}$ | Eng. Cap. | Auto / Man |
|---|---|---|---|---|---|
| kg | kW | g / mL | g / L | L | |
| 7180 | 165 | 2.633 | 830.0 | 4.6 | Manual |

| $f_i$ | A | B | $b_1$ | $b_2$ | $\beta$ |
|---|---|---|---|---|---|
| mL/h | mL/km | mL/km/(km/h)$^2$ | kN | kN/(m/s)$^2$ | mL/kJ |
| 2044 | 179.32 | 0.00042 | 2.0101 | 0.000062 | 0.0892 |

*Figure 3 – Fuel consumption model calibration results for individual vehicles*

***Table 2 - Measured and estimated values of fuel consumption and emission rates for individual test vehicles for the CUEDC-P drive cycle***

| | Fuel Consumption | | $CO_2$ | CO | HC | $NO_X$ |
|---|---|---|---|---|---|---|
| | L/100km | mpg (US) | g/km | g/km | g/km | g/km |
| Small Car: Toyota Corolla Ascent 2004 | | | | | | |
| Measured | 6.0 | 39.2 | 140.1 | 0.229 | 0.010 | 0.068 |
| Estimated | 5.9 | 40.1 | 137.9 | 0.234 | 0.010 | 0.059 |
| Large Car: Holden Commodore 2006 | | | | | | |
| Measured | 9.4 | 24.9 | 220.7 | 0.095 | 0.019 | 0.015 |
| Estimated | 9.3 | 25.4 | 217.8 | 0.093 | 0.016 | 0.012 |
| Truck: Isuzu FVR900 (T) 2005 (Diesel) | | | | | | |
| Measured | 32.0 | 7.3 | 841.8 | 0.951 | 0.083 | 7.577 |
| Estimated | 32.0 | 7.3 | 843.7 | 0.869 | 0.079 | 5.880 |

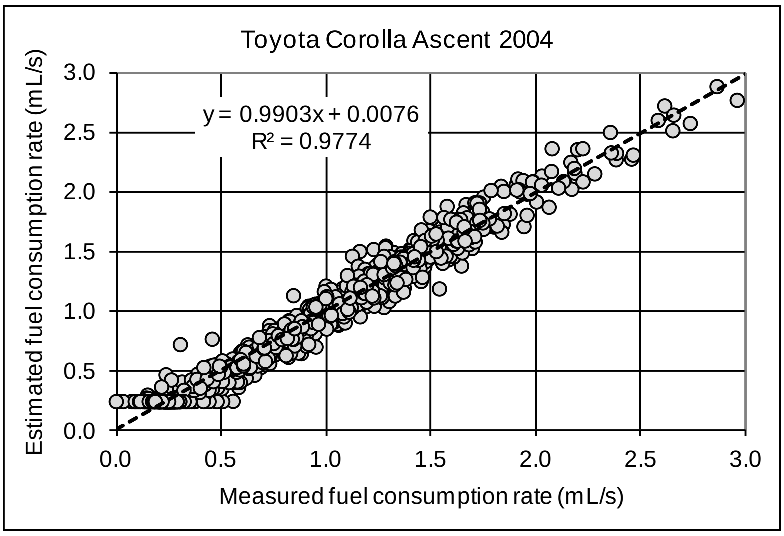

***Figure 4 – Estimated fuel consumption vs measured fuel consumption for Toyota Corolla (vehicle details given in Figure 3) for the CUEDC-P drive cycle (second-by-second fuel consumption values compared)***

Fuel consumption rates estimated using the calibrated test vehicle parameters indicated very high accuracy levels in terms of both instantaneous values. This can be seen from *Figures 4 and 5* which shows comparison of estimated and measured fuel consumption rates for the Toyota Corolla for a section of the drive cycle.

The errors in fuel consumption (and $CO_2$ emission) estimation for the total drive cycle for all vehicles were in the range -3.4 to 0 per cent. The Accuracy levels were high for all segments of the drive cycle *(Residential, Arterial, Freeway and Congested).* The full CUEDC-P drive cycle is also shown in *Figure 5*. On the other hand, the error levels in emission (HC, CO, $NO_x$) estimation were significantly higher (-23.1 to +2.5 per cent for all vehicles).

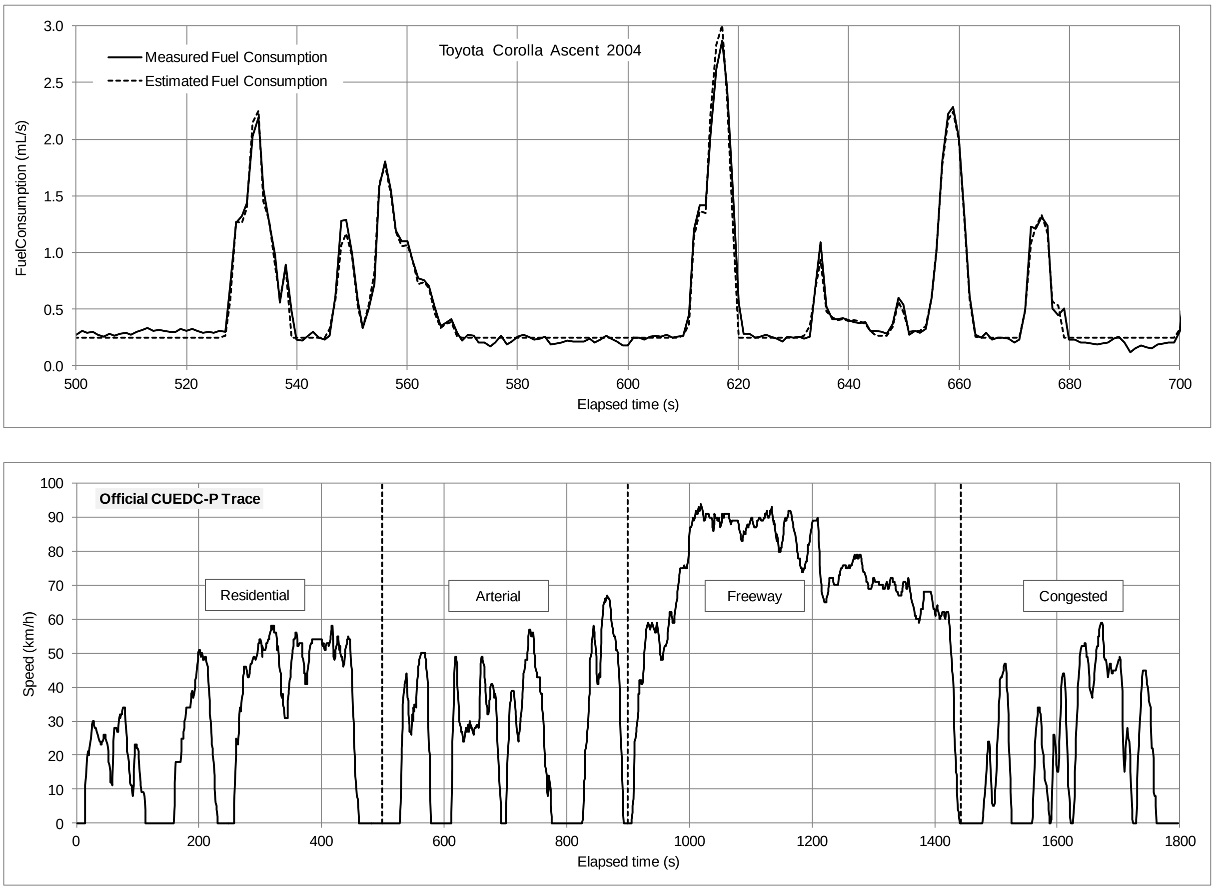

***Figure 5 – Accuracy of the instantaneous fuel consumption model for Toyota Corolla (vehicle details given in Figure 3) with the full CUEDC-P drive cycle also shown***

## COMPARISON OF ALTERNATIVE INTERSECTION TREATMENTS

A case study is used as an example to investigate the implications of the change in model parameters on assessing the effectiveness of roundabout metering signals in terms of fuel consumption and emissions ($CO_2$, HC, CO, $NO_x$) as well as operating costs (including vehicle operating cost and value of time). This is the case of the Nepean Highway - McDonald Street roundabout in Melbourne, Australia. Studies of roundabout metering signals that operate at this intersection were published previously *(27, 36)*. There is extensive literature on roundabout metering signals *(36-45)*. A recent study of emission estimation at multi-lane roundabouts should also be mentioned *(46)*.

This investigation will compare the performance of roundabout metering signals with unsignalised roundabout conditions. Fuel consumption, emission and operating cost results will be obtained using SIDRA INTERSECTION Version 6 with:

(i) older default values for light and heavy vehicles and

(ii) new default values based on the recalibration effort.

The specific purpose of the paper is to investigate whether changes in vehicle parameters change the assessment results significantly.

The example is shown in *Figure 6*. The intersection has been mirror-imaged for driving on the right hand side of the road (to make the example easier to understand for North American readers). The Standard Right-Hand version of the software has been used with the SIDRA Standard roundabout capacity model (Environment Factor = 1.0) in order to emulate the traffic conditions relevant to this case study. Metric units apply. The original AM peak volumes have been increased by 10 per cent. Gap Acceptance Factor and Opposing Vehicle Factor values for Heavy Vehicles are specified as 2.0. Pedestrian movements are not included in the analysis.

Under AM peak conditions, the Nepean Highway SW approach is oversaturated for the unsignalised roundabout (without metering signals) due to unbalanced flow conditions. Metering signals where Nepean Highway SW is the *controlling approach* and McDonald Street NW is the *metered approach* balance the operating conditions on these two approaches introducing significant improvements to the performance of the intersection.

The total fuel consumption, emission and operating cost values as well as various intersection performance indicators (largest degree of saturation, largest 95th percentile back of queue, average intersection delay and the corresponding level of service) are given for the two conditions analyzed. Two sets of total fuel consumption, emission ($CO_2$, HC, CO, $NO_x$) and operating cost values are given corresponding to the use of old and new default values of vehicle parameters for the same intersection performance.

The results of the assessment of the effectiveness of roundabout metering signals using old and new default values of vehicle parameters are summarized in *Table 3*. It is seen that the changes in the default parameters made little difference to the relative levels of benefits obtained from the use of metering signals assessed in terms of fuel consumption, emissions and operating cost results. The differences in fuel consumption and $CO_2$ emissions using the old and new default values were very small whereas the differences in HC, CO and $NO_x$ emissions were very large. While large differences in emission results are as expected due to the effect of emission control technologies, it was surprising to see very small differences in fuel consumption and $CO_2$ emissions (larger differences in $CO_2$ emissions are due to the effect of the change in the $CO_2$ to Fuel Consumption Rate). The main reason for these small differences is the increases in the light vehicle and heavy vehicle mass values. In particular, the composite light vehicle was affected by significant increases in the SUV and light rigid truck percentages in vehicle fleet composition used in determining the mass values for the new defaults.

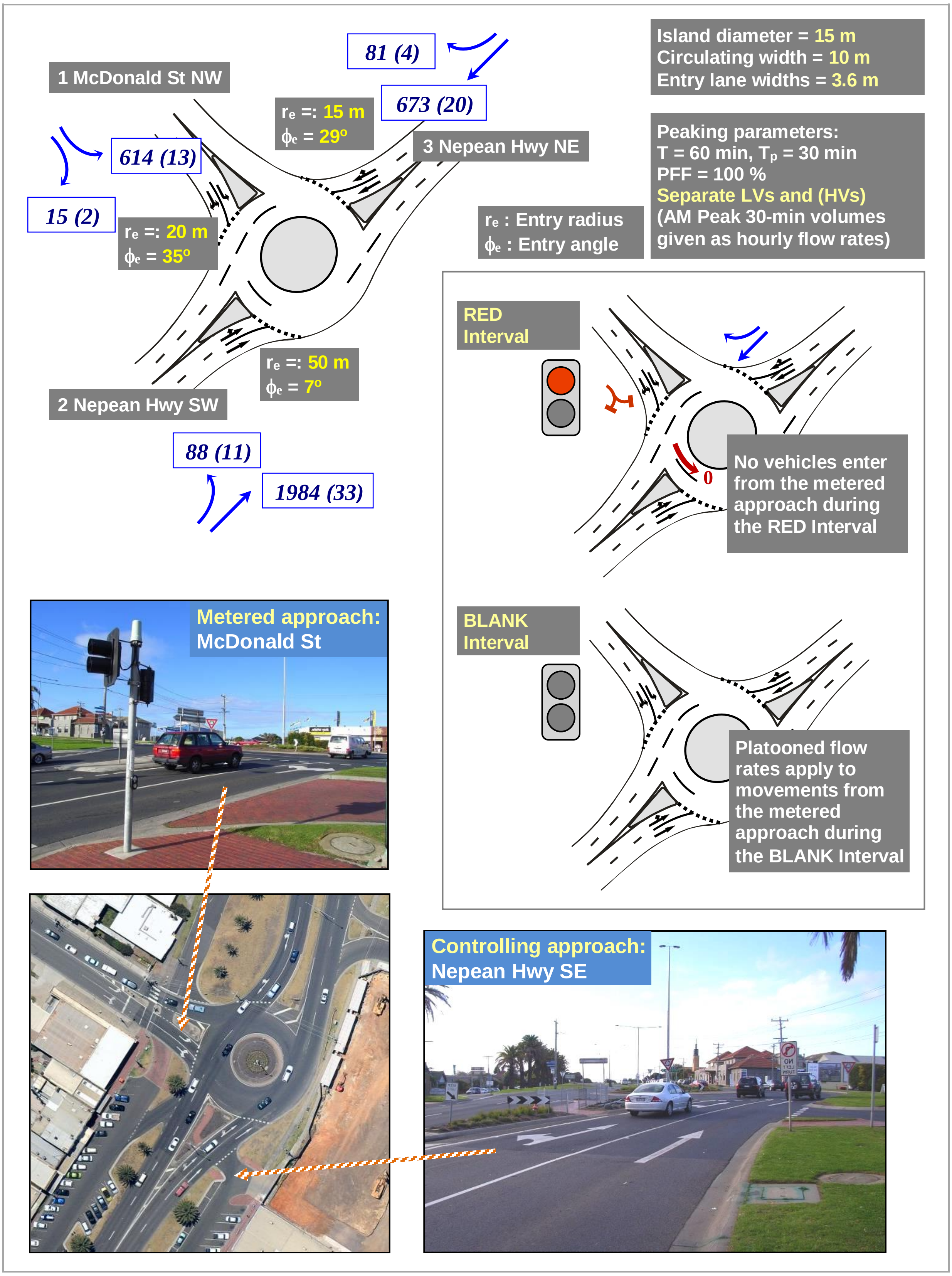

*Figure 6 - Roundabout metering signals case study: Nepean Highway - McDonald Street, Melbourne, Australia*

***Table 3 - Assessment of the effectiveness of roundabout metering signals using old and new default values of vehicle parameters used in the fuel consumption and emission models***

| **Same for OLD and NEW defaults** | | Unsignalized Roundabout | Metering Signals | Metering Benefit |
|---|---|---|---|---|
| Degree of Saturation | | 1.152 | 0.93 | -19.3% |
| Control Delay (Average) | sec | 94.7 | 29.4 | -69.0% |
| Intersection Level of Service (LOS) | | LOS F | LOS C | LOS F to C |
| 95% Back of Queue - Vehicles (Worst Lane) | veh | 113.6 | 35.5 | -68.8% |
| **NEW Defaults** | | Unsignalized Roundabout | Metering Signals | Metering Benefit |
| Cost | $/y | 2,244,932 | 1,255,306 | -44.1% |
| Fuel Consumption | L/y | 232,610 | 179,855 | -22.7% |
| Carbon Dioxide | kg/y | 549,402 | 425,125 | -22.6% |
| Hydrocarbons | kg/y | 54 | 38 | -29.6% |
| Carbon Monoxide | kg/y | 543 | 460 | -15.3% |
| NOx | kg/y | 650 | 531 | -18.3% |
| **OLD Defaults** | | Unsignalized Roundabout | Metering Signals | Metering Benefit |
| Cost | $/y | 2,245,150 | 1,257,159 | -44.0% |
| Fuel Consumption | L/y | 239,315 | 187,195 | -21.8% |
| Carbon Dioxide | kg/y | 599,091 | 468,687 | -21.8% |
| Hydrocarbons | kg/y | 750 | 507 | -32.4% |
| Carbon Monoxide | kg/y | 15,952 | 12,099 | -24.2% |
| NOx | kg/y | 1,153 | 972 | -15.7% |
| **Differences between NEW and OLD defaults** | | Unsignalized Roundabout | Metering Signals | |
| Cost | $/y | 0.0% | -0.1% | |
| Fuel Consumption | L/y | -2.8% | -3.9% | |
| Carbon Dioxide * | kg/y | -8.3% | -9.3% | |
| Hydrocarbons | kg/y | -92.8% | -92.5% | |
| Carbon Monoxide | kg/y | -96.6% | -96.2% | |
| NOx | kg/y | -43.6% | -45.4% | |

* The reduction in the $CO_2$ rate is affected by the new lower default value used.

## CONCLUDING REMARKS

This paper described the instantaneous form of the fuel consumption and emission models, presented the model recalibration results for a number of vehicles, and compared the default vehicle parameters for the composite "Light Vehicle" in SIDRA INTERSECTION before and after recalibration.

A roundabout evaluation case is presented as an example to assess the implications of the change in fuel and emission model parameters. The example evaluates the effectiveness of roundabout metering signals using the fuel consumption and emission models with (i) older vehicle parameter values and (ii) the recalibrated parameter values to investigate whether changes in vehicle parameters change the results significantly.

The results of this investigation indicated that the changes in the default parameters made little difference to the relative levels of benefits obtained from the use of metering signals assessed in terms of fuel consumption, emissions and operating cost results. While the differences in fuel consumption and $CO_2$ emissions using the old and new default values were very small, the differences in HC, CO and $NO_x$ emissions were very large.

Large differences in emission results are as expected due to the effect of emission control technologies. However, it was surprising to see very small differences in fuel consumption and $CO_2$ emissions in view of the decreases in vehicle parameters shown in *Table 1*. The main reason for this finding is the increases in the light vehicle and heavy vehicle mass values. In particular, the new light vehicle mass value was affected by significant increases in the SUV and light rigid truck percentages in vehicle fleet composition. This means that while the energy and $CO_2$ emission efficiencies of modern vehicles are improved, the total fuel consumption and $CO_2$ emissions of the vehicle fleet are not necessarily decreased due to the higher percentage of larger vehicles. Further analyses are recommended using the same (new) vehicle mass values to isolate the effect of other vehicle parameters.

## ACKNOWLEDGEMENTS

The first and third authors are the developers of the SIDRA INTERSECTION and SIDRA TRIP software. The original research on fuel consumption, which forms the basis of the model described in this paper, was conducted by Rahmi Akçelik, David Biggs and Darrell Bowyer. This research received the ITE (USA) 1986 Transportation Energy Conservation Award in Memory of Frederick A. Wagner for research into energy savings from urban traffic management.

## REFERENCES

1. AKÇELIK, R. (1980). Objectives in traffic system management. *Society of Automotive Engineers - Australasia*, 41 (6), pp 284-301.

2. AKÇELIK, R. (1981). Fuel efficiency and other objectives in traffic system management. *Traffic Engineering and Control*, 22 (2), pp 54-65.

3. AKÇELIK, R. (1983). *Progress in Fuel Consumption Modelling for Urban traffic Management*. Research Report ARR No. 124. ARRB Transport Research Ltd, Vermont South, Australia.

4. LUK, J.Y.K. and AKÇELIK, R. (1983). Predicting area traffic control performance with TRANSYT/8 and an elemental model of fuel consumption. *Proc. 12th ARRB Conf. 12 (4)*, pp 87-101.

5. AKÇELIK, R. (1985). An interpretation of the parameters in the simple average travel speed model of fuel consumption. *Australian Road Research* 15 (1), pp 46-49.

6. AKÇELIK, R., BAYLEY, C., BOWYER, D.P. and BIGGS, D.C. (1983). A hierarchy of vehicle fuel consumption models. *Traffic Engineering Control*, 24 (10), pp 491-495.

7. AKÇELIK, R. and BIGGS, D.C. (1985). A discussion on the paper on fuel consumption modelling by Post et al. *Transportation Research* 19B (6), pp 529-533.

8. BIGGS, D.C. and AKÇELIK, R. (1985). Further work on modelling car fuel consumption. *Australian Road Research* 15 (1), pp 46-49.

9. BOWYER, D.P., AKÇELIK, R. and BIGGS, D.C. (1985). *Guide to Fuel Consumption Analysis for Urban Traffic Management*. Special Report SR No. 32. ARRB Transport Research Ltd, Vermont South, Australia.

10. HOLYOAKE, P.A. (1985). *Models for the Effect of Driving and Environmental Conditions on Car Fuel Consumption and Emissions.* Report T76/85. Department of Mechanical and Industrial Engineering, The University of Melbourne, Parkville, Victoria, Australia.

11. AKÇELIK, R. (1986). Models for estimation of car fuel consumption in urban traffic. *ITE Journal*, 56 (7), pp 29-32.

12. AKÇELIK, R. (1986). Discussion on the paper 'Estimating fuel consumption from engine size' by T.N. Lam. *Journal of Transportation Engineering*, 113 (1), pp 101-106.

13. BIGGS, D.C. and AKÇELIK, R. (1986). An energy-related model of instantaneous fuel consumption. *Traffic Engineering and Control*, 27 (6), pp 320-325.

14. BIGGS, D.C. and AKÇELIK, R. (1986). Estimation of car fuel consumption in urban traffic. *Proc. 13th ARRB Conf*. 13 (7), pp 123-132.

15. BOWYER, D.P., AKÇELIK, R. and BIGGS, D.C. (1986). Fuel consumption analyses for urban traffic management. *ITE Journal*, 56 (12), pp 31-34.

16. AKÇELIK, R. and BIGGS, D.C. (1987). Acceleration profile models for vehicles in road traffic. *Transportation Science*, 21 (1), pp. 36-54.

17. BIGGS, D.C. (1988). *ARFCOM – Models for Estimating Light to Heavy Vehicle Fuel Consumption*. Research Report ARR No. 152. ARRB Transport Research Ltd, Vermont South, Australia.

18. AKÇELIK, R. (1989). Efficiency and drag in the power-based model of fuel consumption. Transportation Research 23B (5), pp 373-385.

19. TAYLOR, M.P. and YOUNG, T. (1996). Developing a set of fuel consumption and emissions models for use in traffic network modelling. *Proceedings of the 13th International Symp. on Transportation and Traffic Theory*. (Ed. J-B. Lesort). Pergamon, Elsevier Science, Oxford 1996, pp 289-314.

20. AKÇELIK, R. and BESLEY M. (2001). Acceleration and deceleration models. *23rd Conference of Australian Institutes of Transport Research (CAITR 2001)*, Monash University, Melbourne, Australia.

21. AKÇELIK, R. and BESLEY, M. (2003). Operating cost, fuel consumption, and emission models in aaSIDRA and aaMOTION. *25th Conference of Australian Institutes of Transport Research (CAITR 2003)*, University of South Australia, Adelaide, Australia.

22. AKCELIK AND ASSOCIATES (2007). *SIDRA TRIP User Guide (for Version 1.0).* Akcelik and Associates Pty Ltd, Melbourne, Australia.

23. AKCELIK AND ASSOCIATES (2014). *SIDRA INTERSECTION User Guide (for Version 6.0).* Akcelik and Associates Pty Ltd, Melbourne, Australia.

24. MUSTAFA, M.A.S and VOUGIAS, S. (1993). Analysis of pollutant emissions and concentrations at urban intersections. *Compendium of Technical Papers, ITE 63rd Annual Meeting*, pp 234-238.

25. REDINGTON, T. (2001). Modern roundabouts, global warming and emissions reductions: Status of research and opportunities for North America. *The Canadian Transportation Research Forum, 36th Annual Conference*, Vancouver, British Columbia, Canada, 2001.

26. MANDAVILLI, S., RYS, M.J. and RUSSELL, E.R. (2008). Environmental Impact of modern roundabouts. *International Journal of Ergonomics*, 38 (2), pp 135-142.

27. AKÇELIK, R. (2006). Operating Cost, Fuel Consumption and Pollutant Emission Savings at a Roundabout with Metering Signals. *ARRB 22nd Conference*, Canberra, Australia.

28. UNAL, A., FREY, H.C., ROUPHAIL, N.M. and COLYAR, J.D. (2003). Effects of traffic flow and signal control on measured vehicle emissions. *82nd Annual Meeting of Transportation Research Board*, Washington, D.C, U.S.A.

29. AKÇELIK, R., SMIT, R. and BESLEY, M. (2012). Calibrating fuel consumption and emission models for modern vehicles. *IPENZ Transportation Group Conference*, Rotorua, New Zealand.

30. DEHWA (2005). *NISE 2 Contract 2 Drive Cycle and Short Test Development*, Department of the Environment and Heritage, Canberra, Australia.

31. DEHWA (2009). *Second National In-Service Emissions Study (NISE 2) Light Duty Petrol Vehicle Emissions Testing*. Prepared by Roads and Traffic Authority of NSW, RTA. 07.2828.0309.

32. SMIT, R., STEELE, J. and WILSON, M. (2010). *Project 1: Vehicle Emissions Factor Development - NISE 2 Data Verification*. Report prepared for the Road Traffic Authority (RTA), PAE Holmes Report No. 3909.

33. TRB (2010). *Highway Capacity Manual*. Transportation Research Board, National Research Council, Washington, DC, USA.

34. AKÇELIK, R. (1994). Gap acceptance modelling by traffic signal analogy. *Traffic Engineering and Control*, 35 (9), pp 498-506.

35. AKÇELIK, R. (2007). A Review of Gap-Acceptance Capacity Models. *29th Conference of Australian Institutes of Transport Research (CAITR)*, University of South Australia, Adelaide, Australia.

36. AKÇELIK, R. (2011). Roundabout metering signals: capacity, performance and timing. *6th International Symposium on Highway Capacity and Quality of Service*, Transportation Research Board, Stockholm, Sweden. *Procedia - Social and Behavioural Sciences, Vol 16*, pp 686-696.

37. HUDDART, K.W. (1983). Signaling of Hyde Park Corner, Elephant and Castle and other roundabouts. *PTRC Summer Annual Meeting, Proceedings of Seminar K*, 1983, pp 193-208.

38. AKÇELIK, R., CHUNG, E. and BESLEY M. (1997). Analysis of Roundabout Performance by Modelling Approach Flow Interactions. In: Kyte, M. (Ed.), *Proceedings of the Third International Symposium on Intersections Without Traffic Signals*, July 1997, Portland, Oregon, USA, University of Idaho, Moscow, Idaho, USA, pp 15-25.

39. AKÇELIK, R. (2003). A Roundabout Case Study Comparing Capacity Estimates from Alternative Analytical Models. *2nd Urban Street Symposium*, Anaheim, California, USA.

40. AKÇELIK, R. (2004). Roundabouts with Unbalanced Flow Patterns. *ITE Annual Meeting*, Lake Buena Vista, Florida, USA.

41. AKÇELIK, R. (2005). Roundabout Model Calibration Issues and a Case Study. *TRB National Roundabout Conference*, Vail, Colorado, USA.

42. AKÇELIK, R. (2005). Capacity and Performance Analysis of Roundabout Metering Signals. *TRB National Roundabout Conference*, Vail, Colorado, USA.

43. NATALIZIO, E. (2005). Roundabouts with Metering Signals. *ITE Annual Meeting*, Melbourne, Australia.

44. AKÇELIK, R. (2008). An investigation of the performance of roundabouts with metering signals. *National Roundabout Conference*, Transportation Research Board, Kansas City, MO, USA.

45. AKÇELIK, R. (2009). *Evaluating Roundabout Capacity, Level of Service and Performance*. *ITE Annual Meeting*, San Antonio, Texas, USA.

46. SALAMATI, K., et al (2013). Emissions estimation at multilane roundabouts. *Transportation Research Record* 2389, pp 12-21. Transportation Research Board, National Research Council, Washington, DC, USA.