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aaMotion has been subsequently named SIDRA TRIP and released during December 2007.

Operating cost, fuel consumption, and emission models in aaSIDRA and aaMOTION

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1 INTRODUCTION

Estimation of operating cost, fuel consumption and pollutant emissions for evaluating intersection and mid-block traffic conditions is useful for design, operations and planning purposes in traffic management. This paper describes the method to model operating cost, fuel consumption and emissions (CO_2, CO, HC, NO_x) in the aaSIDRA intersection analysis and aaMOTION trip / drive-cycle simulator software packages developed by Akcelik & Associates.

aaSIDRA is an intersection analysis package first released in 1984. The latest version is aaSIDRA 2.0 (Akcelik & Associates 2002). aaMOTION for general traffic assessment purposes is a single-vehicle microscopic simulation package that uses a time-step simulation model. It has not been released yet.

aaSIDRA uses a four-mode elemental model to estimate fuel consumption and pollutant emissions. The operating cost includes the *direct vehicle operating cost* (resource cost of fuel and additional running costs including tyre, oil, repair and maintenance) and the *time cost* for persons in vehicles.

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The fuel consumption estimate is converted to direct vehicle operating cost. The time cost is calculated using vehicle occupancy, average income and a time value factor that converts the average income to a value of time. Operating cost for pedestrians includes the time cost only.

aaMOTION uses an instantaneous model to estimate operating cost, fuel consumption and emissions. The four mode elemental model used in aaSIDRA is derived from the instantaneous model and uses essentially the same vehicle parameters (Akçelik, et al 1983; Bowyer, Akçelik and Biggs 1985).

The models used in aaSIDRA and aaMOTION are based on extensive research (Akçelik 1980, 1981, 1983, 1985, 1986a,b, 1989; Akçelik, et al 1983; Akçelik and Biggs 1985; Biggs 1988; Biggs and Akçelik 1985, 1986a,b; Bowyer, Akçelik and Biggs 1985, 1986; Holyoake 1985; Luk and Akçelik 1983; Taylor and Young 1996). The main features of these models are summarised in this paper.

2 MODEL PARAMETERS

The fuel consumption, emission and operating cost models use two groups of parameters:

(i) vehicle parameters,

(ii) traffic and road parameters, and

(iii) cost parameters

Vehicle parameters include loaded mass, idle fuel or emission rates, fuel or emission efficiency rates. The vehicle parameters used in the fuel consumption and emission models are derived considering vehicle composition (percentage of vehicle kilometers 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.

Fuel consumption, emissions and cost are calculated for *Light and Heavy Vehicles*. 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 defines a Heavy Vehicle as "a vehicle with more than four wheels touching the pavement during normal operation" (TRB 2000). 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).

In aaMOTION, vehicle parameters can be specified for individual vehicles.

Traffic and road parameters include speed, acceleration rate and grade parameters. Cost parameters include the pump price of fuel, fuel resource cost factor, running cost/fuel cost ratio, average income, and the time value factor as a proportion of average hourly income.

Model parameters for fuel consumption and various emission rates are given in *Table 2.1*. Some fuel consumption model parameters given in *Table 2.1* are based on those reported in Bowyer, Akçelik and Biggs (1985), and the emission model parameters are based on those derived by Holyoake (1985).

Detailed data used for the selection of representative Light and Heavy vehicles are presented in *Table 2.2*. Heavy vehicle parameters represent a mixture of vehicles that use petrol and diesel fuel (70 per cent diesel use for the selected vehicle composition) as seen in *Table 2.2*.

Operating cost model parameters (default values for Australia, New Zealand and USA) are given in *Table 2.3*.

Table 2.1

Parameters for fuel consumption and emission models

Parameter	Description	Unit for Fuel	Unit for Emissions	**Fuel**	**CO**	**HC**	**NO_x**
f_i	Idle fuel consumption or emission rate	mL/h	g/h	1350 (LV) 2000 (HV)	50	8	2
$10^4\,\beta_1$	Efficiency parameter	mL/kJ	g/kJ	900 (LV) 800 (HV)	150	0	10
$10^4\,\beta_2$	Energy-acceleration efficiency parameter	mL/ (kJ.m/s^2)	g/ (kJ.m/s^2)	300 (LV) 200 (HV)	250	4	2
M_{vLV}	Average vehicle mass for light vehicles (cars, vans)	kg	kg	1400	1400	1400	1400
M_{vHV}	Average vehicle mass for heavy vehicles (trucks, buses)	kg	kg	11000	11000	11000	11000
CO_2 rates in grams per millilitre of fuel: Light vehicles: f_{CO2LV} = 2.5 g/mL Heavy vehicles: f_{CO2HV} = 2.6 g/mL							

The parameter vales are used for both light vehicles (LV) and heavy vehicles (HV) unless indicated otherwise.

For symbols, see Sections 4 and 5.

Table 2.2

Data for representative Light and Heavy Vehicles for urban traffic

Vehicle Class	Percentage of Vehicle Kilometres	Fuel type (% Diesel)	Idle fuel cons. (mL/h)	Loaded mass, M (kg)	Max engine power (kW)
Light Vehicles					
Small car	30%	1	900	1100	64
Medium car	30%	2	1296	1250	80
Large car	30%	2	1728	1500	110
Van	8%	13	1728	2000	70
Light rigid	2%	34	1332	2700	75
Combined	100%	3	1342	1369	83
Selected		**3**	**1350**	**1400**	**85**
Heavy Vehicles					
Light/Medium rigid	60%	48	1620	5500	90
Medium rigid	15%	87	1800	10000	120
Medium/heavy truck	15%	98	2340	16000	170
Heavy truck	5%	100	2520	28000	260
Heavy articulated	5%	100	2520	38000	300
Combined	100%	67	1980	10500	126
Selected		**70**	**2000**	**11000**	**130**

Vehicle Class	No. of wheels	Tyre diameter (m)	Rolling res. factor for tyre type	Frontal area (m^2)	Aero. drag coefficient (with wind factor 1.2)
Light Vehicles					
Small car	4	0.65	1.00	1.8	0.50
Medium car	4	0.65	1.00	2.0	0.53
Large car	4	0.65	1.00	2.2	0.55
Van	4	0.65	1.05	2.6	0.62
Light rigid	4	0.80	1.25	4.0	0.66
Combined	4	0.65	1.01	2.1	0.54
Selected	**4**	**0.65**	**1.00**	**2.1**	**0.54**
Heavy Vehicles					
Light/Medium rigid	6	0.80	1.20	5.0	0.70
Medium rigid	6	1.00	1.15	6.0	0.72
Medium/heavy truck	10	1.00	1.10	6.5	0.77
Heavy truck	18	1.00	1.05	7.0	0.82
Heavy articulated	22	1.00	1.05	8.0	0.86
Combined	8	0.88	1.16	5.6	0.72
Selected	**8**	**0.90**	**1.15**	**5.6**	**0.72**

Table 2.3

Default values of cost model parameters for Australia, New Zealand and US

Parameter	Symbol	Australia	New Zealand	USA
Cost Unit		$ (AUD)	$ (NZD)	$ (USD)
Parameters for operating cost factor	(k_o)			
Pump price of fuel in "Cost Unit" per litre (or per gallon)	(P_p)	0.85 ($/L)	1.05 ($/L)	$ 0.40 ($/L) (1.60 $/gal)
Fuel resource cost factor	(f_r)	0.50	0.60	0.70
Running cost/fuel cost ratio	(f_c)	3.0	2.5	3.0
Parameters for time cost	(k_t)			
Average income (full time adult average hourly total earnings) in "Cost Unit" per hour	(W)	23.00 ($/h)	18.00 ($/h)	17.00 ($/h)
Time value factor as a proportion of average hourly income	(f_p)	0.60	0.60	0.40
Average occupancy in persons per vehicle	(f_o)	1.5	1.5	1.2
Calculated values				
Vehicle operating cost factor in "Cost Unit" per litre (or per gallon) of fuel	$(k_o = f_c\ f_r\ P_p)$	1.275 ($/L)	1.575 ($/L)	0.840 ($/L) (3.36 $/gal)
Time cost per ***person*** in "Cost Unit" per hour	$(f_p\ W)$	13.80 ($/h)	10.80 ($/h)	6.80 ($/h)
Time cost per ***vehicle*** in "Cost Unit" per hour	$(k_t = f_o\ f_p\ W)$	20.70 ($/h)	16.20 ($/h)	8.16 ($/h)
Vehicle parameters				
Light Vehicle Mass (average value in kg or lb)	(M_{vLV})	1400	1400	1400 (3100 lb)
Heavy Vehicle Mass (average value in kg or lb)	(M_{vHV})	11000	11000	11000 (24,000 lb)
Idle fuel consumption rate for Light Vehicles in millilitres per hour (or gallons per hour)	(f_{iLV})	1350	1350	1350 (0.360 gal/h)
Idle fuel consumption rate for Heavy Vehicles in millilitres per hour (or gallons per hour)	(f_{iHV})	2000	2000	2000 (0.530 gal/h)

For symbols, see Sections 4 and 5.

3 DATA and MODELS

aaMOTION traffic data is based on:

(i) microscopic (usually second-by-second) *trip data from an instrumented car*, e.g. data collected using a Global positioning System (GPS) data logger,

(ii) microscopic (usually second-by-second) trip data representing a *standard drive cycle*, or

(iii) drive-cycle data generated by the user to represent a series of *traffic events* which are specified in terms of cruise, idle and speed change (acceleration or deceleration) with initial and final speeds given for each event.

In all cases, aaMOTION generates instantaneous speed and acceleration rate values for use by the microscopic simulation model. Fuel consumption, pollutant emissions and operating cost are calculated for each simulation interval (time step), and the results added together for each drive-cycle element (event) and for the entire trip.

aaSIDRA uses a macroscopic four-mode elemental (drive cycle) model. For each lane of traffic, the model derives drive cycles consisting of a series of *cruise*, *acceleration*, *deceleration* and *idling (stopped) time* elements for specific traffic conditions represented by intersection geometry, traffic control and demand flows based on data supplied by the user (see *Figure 3.1*). Thus, the drive cycles generated by aaSIDRA are very different for different intersection types (signalised, sign-controlled, roundabout), for different signal phasing arrangements, 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.

Fuel consumption values are calculated for each of the four driving modes, and the results added together for the entire driving manoeuvre from entry to the approach road at a point upstream of the intersection to a point on the downstream exit road. The model is applied to queued (stopped) and unqueued (unstopped) vehicles, and light and heavy vehicles in each lane separately, and then the total values are calculated for all traffic using the lane. For unqueued vehicles, only the cruise and geometric stop (intersection negotiation) components apply. For queued vehicles, the drive cycles are determined distinguishing between major stops, queue move-ups (repeated stops in queue) and geometric stops (slow-down or full stop in the absence of any other vehicle).

The instantaneous models of fuel consumption, emissions and operating cost are described in the following sections.

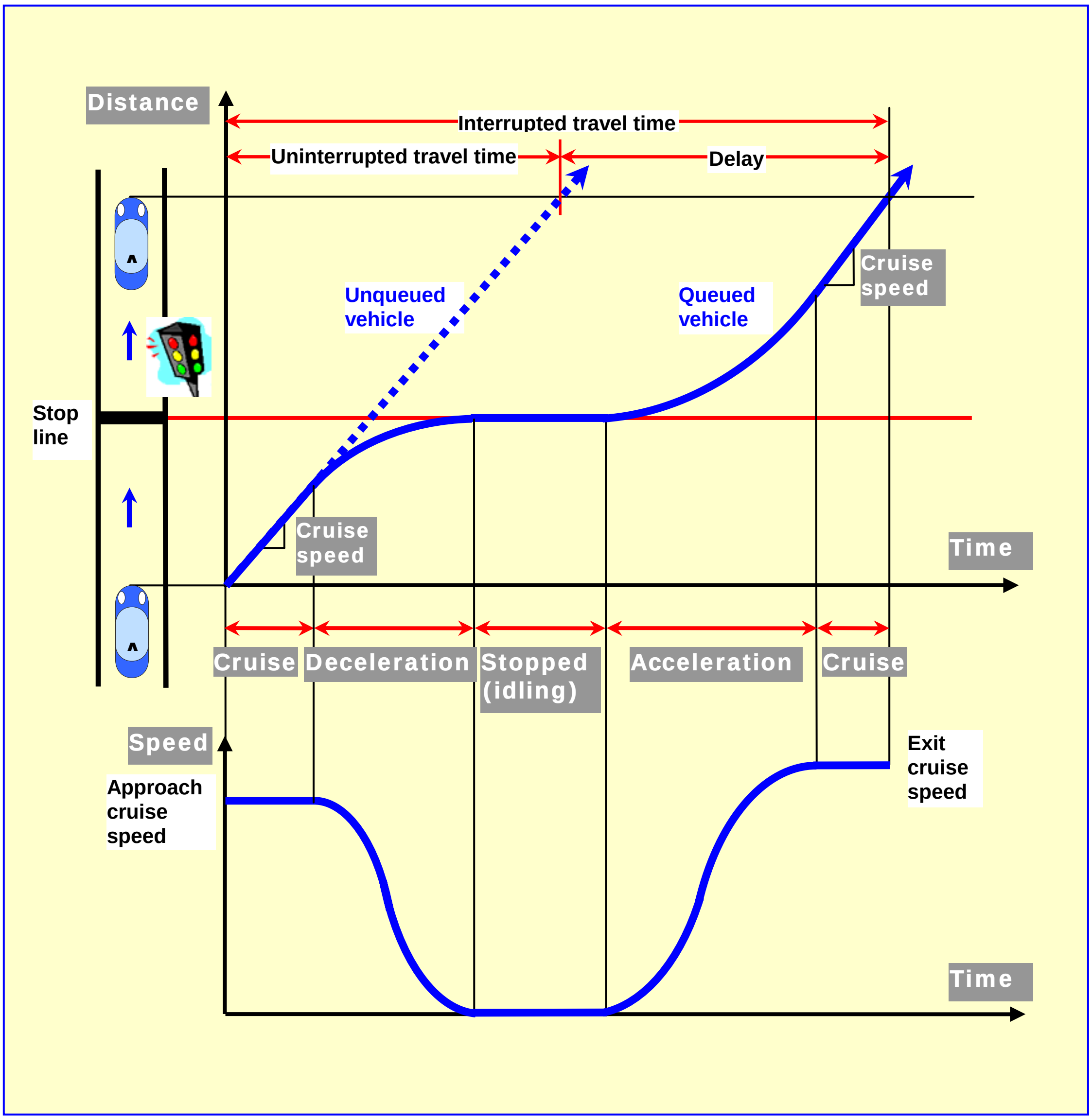

Figure 3.1 - Drive cycle during a stop at traffic signals (example)

4 FUEL CONSUMPTION and EMISSIONS

The following function is used to estimate the value of the fuel consumed (mL) or emission produced (g), ΔF, during a simulation interval (duration Δt seconds):

$$\Delta F = \{\alpha + \beta_1 R_T v + [\beta_2 M_v a^2 v / 1000]_{a>0}\} \Delta t \quad \text{for } R_T > 0 \qquad (4.1)$$
$$= \alpha \Delta t \quad \text{for } R_T \leq 0$$

where

R_T = total tractive force (kN) required to drive the vehicle, which is the sum of rolling resistance, air drag force, cornering resistance, inertia force and grade force,

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,

α = constant idle fuel rate (mL/s) or emission rate (g/s), which applies during all modes of driving (as an estimate of fuel used to maintain engine operation),

β_1 = the efficiency parameter which relates fuel consumed or pollutant emitted to the energy provided by the engine, i.e. fuel consumption or emission per unit of energy (mL/kJ or g/kJ), and

β_2 = the efficiency parameter which relates fuel consumed or pollutant emitted during positive acceleration to the product of inertia energy and acceleration, i.e. fuel consumption or emission per unit of energy-acceleration (mL/(kJ.m/s^2) or g/(kJ.m/s^2)).

Equation (4.1) represents an energy or power-based fuel consumption or emission model, where the total tractive power, P_T and inertial power, P_I (kW) are:

$$P_T = R_T v \qquad (4.2)$$
$$P_I = M_v a v / 1000$$

Models for estimating the instantaneous *Carbon Monoxide (CO)*, *Hydrocarbons (HC)* and *Nitrogen Oxides (NO_x)* emissions have the same structure as the instantaneous fuel consumption model (*Equation 4.1*) with different parameters (see *Table 2.1*).

The values of *Carbon Dioxide (CO_2)* emission are estimated directly from fuel consumption estimates:

$$\Delta F (CO_2) = f_{CO2} \Delta F (fuel) \qquad (4.3)$$

where

ΔF (*fuel*) = fuel consumption in mL calculated from *Equation (4.1)* and,

f_{CO2} = CO_2 rate in grams per millilitre of fuel (g/mL) from *Table 2.1*.

Instantaneous fuel consumption rate (mL/s) and *instantaneous emission rate* (g/s) at any simulation time step, f_t, are calculated as:

$$f_t = \Delta F / \Delta t \qquad (4.4)$$

where ΔF is from *Equation (4.1)*.

5 OPERATING COST

The operating cost estimate includes the *direct vehicle operating cost* (resource cost of fuel and additional running costs including tyre, oil, repair and maintenance as a factor of the cost of fuel), and the *time cost*. For this purpose, an *operating cost factor* (k_o) and a *time cost per vehicle* (k_t) are calculated.

The cost model parameters include Cost Unit (user's own currency), Pump Price of Fuel, Fuel Resource Cost Factor, Ratio of Running Cost to Fuel Cost, Average Income, Time Value Factor, Average Occupancy (persons/veh). Vehicle parameters used in fuel consumption estimation are also relevant, including Vehicle Mass and Idle Fuel Rate parameters. *Table 2.3* gives the default cost model parameters for Australia, New Zealand and US. The values calculated for parameters (k_o and k_t) are also given in *Table 2.3*.

Operating cost for a vehicle during a simulation interval (duration Δt) is ΔC in *Cost Units*. This is calculated from:

$$\Delta C = k_o \, \Delta F / 1000 + k_t \, \Delta t / 3600 \qquad (5.1)$$

where

ΔF = fuel consumption (mL) during Δt from *Equation (4.1)*,

Δt = duration of simulation interval (seconds), and

k_o and k_t are determined from *Equations (5.2) and (5.3)*.

The operating cost factor, k_o ("Cost Unit" per litre or per gallon of fuel, e.g. $/L or $/gal) is calculated from:

$$k_o = f_c \, f_r \, P_p \qquad (5.2)$$

where

f_c = a cost factor used to convert the cost of fuel to total running cost including tyre, oil, repair and maintenance;

f_r = fuel resource cost factor (ratio of the resource price of fuel to the pump price); resource price is the wholesale price plus retail margin less taxes;

P_p = pump price of fuel in "Cost Unit" per litre (per gallon if US Customary Units are used), e.g. $/L or $/gal.

The time cost per vehicle, k_t in "Cost Unit" per hour, e.g. $/h, is calculated from:

$$k_t = f_o \, f_p \, W \qquad (5.3)$$

where

f_o = average occupancy in persons per vehicle;

f_p = time value factor that converts the average income to a value of time;

W = average income (full time adult average hourly total earnings) in "Cost Unit" per hour, e.g. $/h.

Instantaneous operating cost rate (*Cost Units*/s) at any simulation time step, c_t, is calculated as:

$$c_t = \Delta C / \Delta t \qquad (5.4)$$

where ΔC is from *Equation (5.1)*. Therefore:

$$c_t = k_o f_t /1000 + k_t / 3600 \quad (5.5)$$

where f_t is the instantaneous fuel consumption rate from *Equation (4.4)*.

Equations (5.1), (5.4) and (5.5) can be used to determine the total trip cost and the trip cost rate by employing total trip fuel consumption and cost instead of the instantaneous value of fuel consumption (ΔF) and cost (ΔC) and total travel time instead of the duration of simulation interval (Δt).

6 MODEL OUTPUT

Examples of model output presenting operating cost, fuel consumption and pollutant emission estimates from aaSIDRA and aaMOTION are given in *Figures 6.1 to 6.3*.

7 CONCLUSION

The instantaneous model used in aaMOTION and the four-mode elemental model based on drive cycles (also called *modal* model) used in aaSIDRA provide highly accurate fuel consumption or emission models for traffic analysis since there is no aggregation (simplification) involved in terms of traffic information, i.e. such variables as average travel speed, average running speed, number of stops, etc. are not used (Bowyer, Akçelik and Biggs 1985; Taylor and Young 1996).

While the traffic parameters, vehicle parameters, and cost parameters used in these models are highly reliable, further research into vehicle parameters, particularly for pollutant emission models, is recommended to reflect the changes in vehicle characteristics and the vehicle composition (e.g. see Unal, Frey, Rouphail and Colyar 2003).

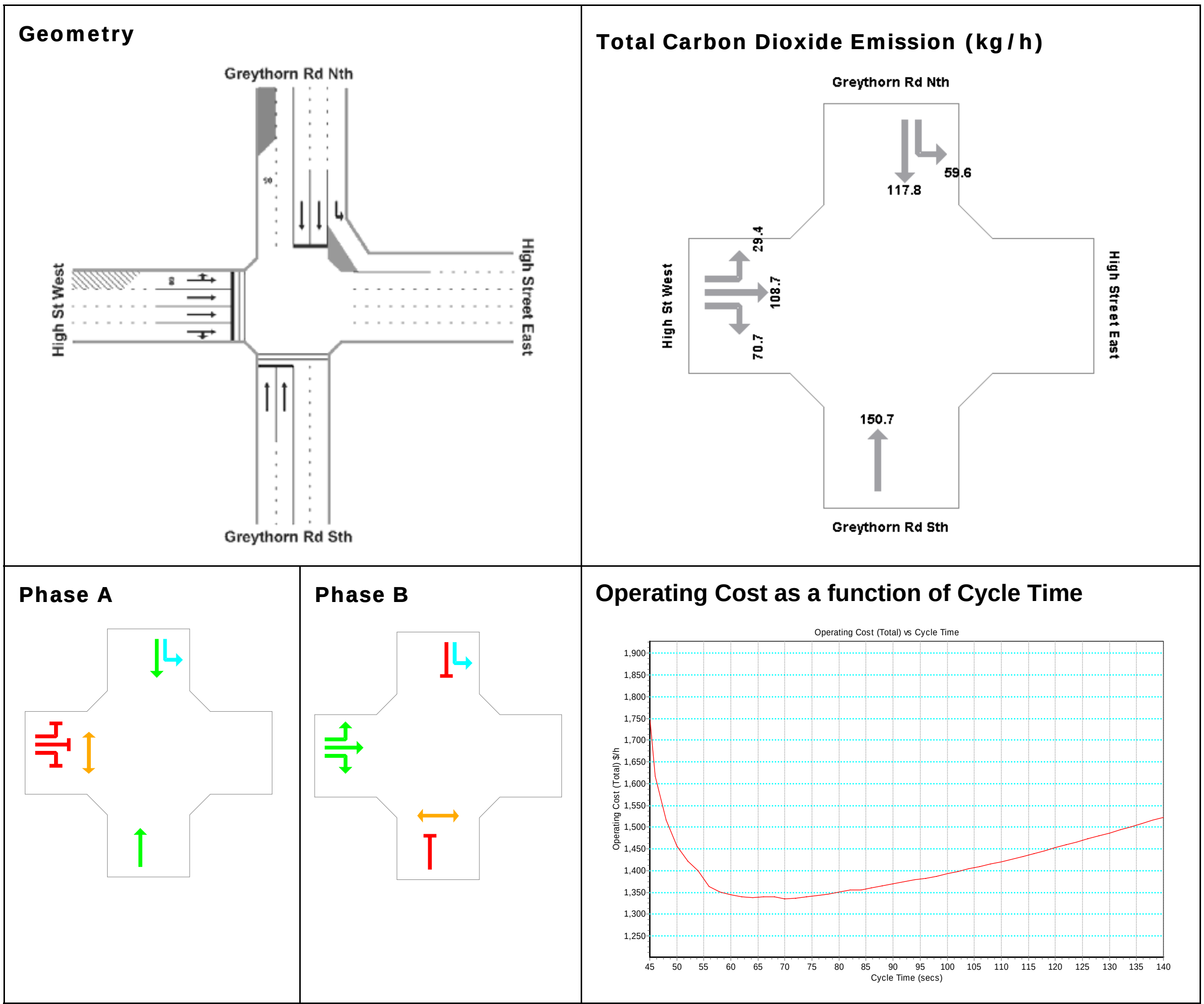

Table S.12A - FUEL CONSUMPTION, EMISSIONS AND COST - TOTAL

Mov No.	Fuel Total L/h	Cost Total $/h	HC Total kg/h	CO Total kg/h	NOX Total kg/h	CO2 Total kg/h
South: Greythorn Rd Sth						
2 T	60.1	364.52	0.261	12.46	0.342	150.7
	60.1	364.52	0.261	12.46	0.342	150.7
North: Greythorn Rd Nth						
7 L	23.8	127.15	0.093	4.65	0.136	59.6
8 T	47.0	278.19	0.197	9.19	0.260	117.8
	70.8	405.34	0.291	13.84	0.396	177.4
West: High St West						
10 L	11.7	72.43	0.050	2.39	0.067	29.4
11 T	43.4	261.83	0.184	8.56	0.240	108.7
12 R	28.2	198.07	0.128	5.66	0.155	70.7
	83.3	532.34	0.363	16.61	0.462	208.8
ALL VEHICLES:	214.2	1302.19	0.914	42.91	1.200	536.8

Figure 6.1 - Example of aaSIDRA output related to operating cost, fuel consumption and emission rates

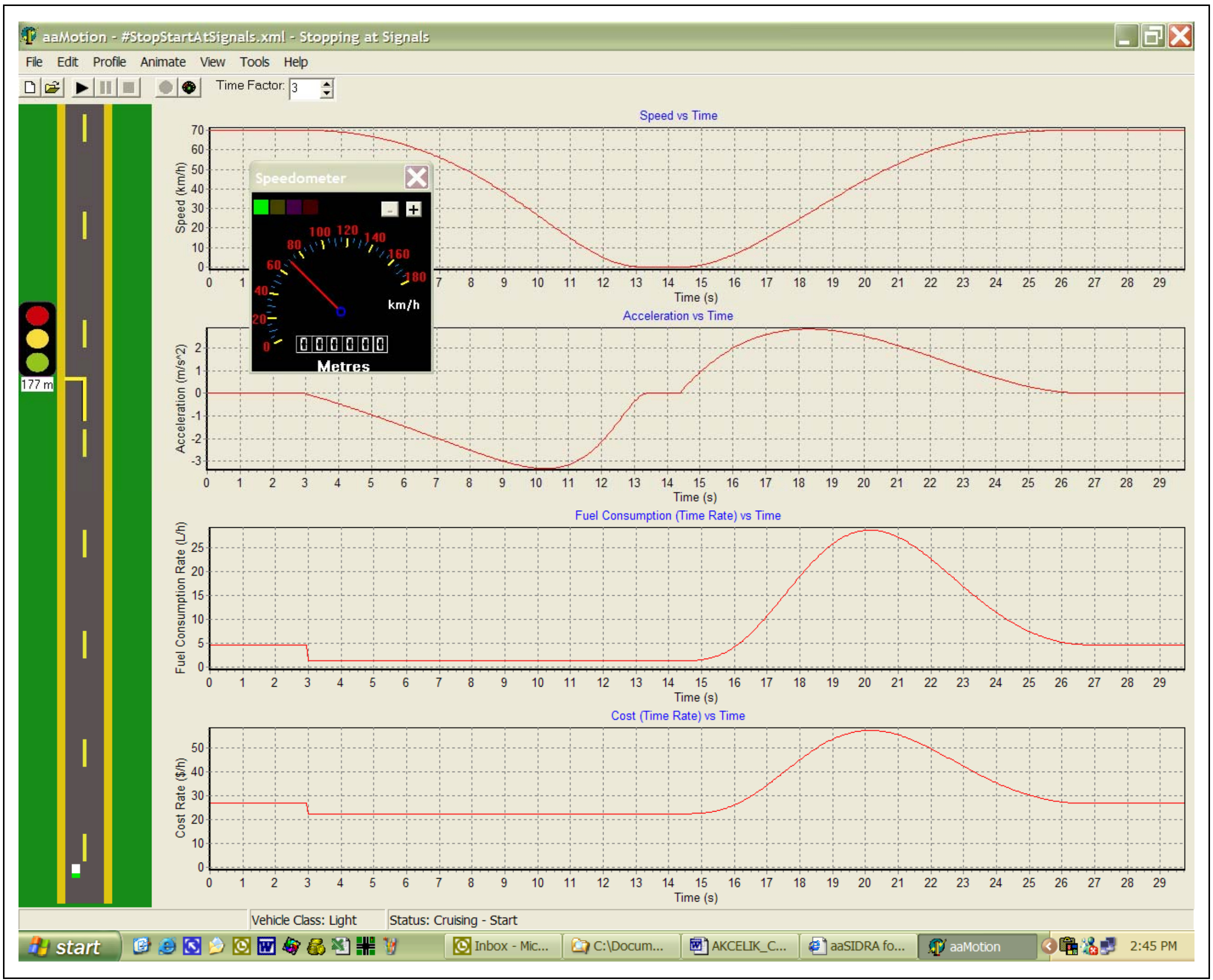

Figure 6.2 - Example of aaMOTION graphs related to operating cost and fuel consumption

Trip Statistics

Stopping at Signals

Travel Distance, Time and Delay

Total Travel Distance	= 380.07	m
Total Travel Time	= 29.75	s
Travel Time per km	= 78.28	s/km
Travel Delay	= 10.20	s
Travel Delay per km	= 26.85	s/km

Speed

Average Travel Speed	= 45.9	km/h
Average Running Speed	= 47.6	km/h
Highest Speed	= 70.0	km/h
Lowest Speed	= 0.0	km/h
Desired Speed	= 70.0	km/h

Operating Cost

Trip Total	= 0.25	$
Average Time Rate	= 30.201	$/h
Average Distance Rate	= 0.658	$/km
Excess Cost	= 0.14	$
Excess Cost per km	= 0.36	$/km

Fuel Consumption

Trip Total	= 62.65	mL
Average Time Rate	= 7.568	L/h
Average Distance Rate	= 6.067	km/L
Average Distance Rate	= 16.484	L/100km
Excess Fuel	= 37.10	mL
Excess Fuel per km	= 97.60	mL/km

CO2 Emission

Trip Total	= 156.62	g
Average Time Rate	= 18.921	kg/h
Average Distance Rate	= 412.082	g/km
Excess CO2	= 92.74	g
Excess CO2 per km	= 244.01	g/km

NOx Emission

Trip Total	= 0.45	g
Average Time Rate	= 0.054	kg/h
Average Distance Rate	= 1.184	g/km
Excess NOx	= 0.33	g
Excess NOx per km	= 0.86	g/km

Figure 6.3 - Example of aaMOTION trip statistics related to operating cost, fuel consumption and emission rates

DISCLAIMER

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