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OPERATING COST, FUEL CONSUMPTION AND POLLUTANT EMISSION SAVINGS AT A ROUNDABOUT WITH METERING SIGNALS

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ABSTRACT

Estimation of operating cost, fuel consumption and pollutant emissions for evaluating intersection traffic conditions is useful for design, operations and planning purposes in traffic management. A four-mode elemental (drive cycle) model is used for estimating fuel consumption, emissions and operating cost. The drive cycles vary significantly for different intersection types (roundabout, signalised, sign-controlled), for different signal phasings and timings, and for different congestion levels. A case study is presented comparing a roundabout with and without metering signals in terms of operating cost, fuel consumption and pollutant emissions as well as delay and degree of saturation. When low capacity conditions occur during peak demand flow periods, the use of part-time metering signals is a cost-effective measure to avoid the need for a fully-signalized intersection treatment. The case study shows the effectiveness of this method of traffic control.

INTRODUCTION

Estimation of operating cost, fuel consumption and pollutant emissions in evaluating intersection and mid-block traffic conditions is useful for design, operations and planning purposes in traffic management. This paper presents a case study comparing a roundabout with and without metering signals in terms of operating cost, fuel consumption and pollutant emissions. The analyses were carried out using the SIDRA INTERSECTION software package (Akcelik & Associates 2006).

The method to model operating cost, fuel consumption and emissions (CO_2, CO, HC, NO_x) in the SIDRA INTERSECTION (also known as SIDRA or aaSIDRA) and SIDRA TRIP (previously known as aaMotion) software packages is described in some detail in Akçelik and Besley (2003). The method is 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 MODEL

The SIDRA INTERSECTION software uses a four-mode (cruise, deceleration, idling, acceleration) elemental model to estimate fuel consumption, pollutant emissions and operating cost. The model employs three groups of parameters, namely vehicle parameters, traffic and road parameters, and cost parameters.

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

Fuel consumption, emissions and cost are calculated for light and heavy vehicles. 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 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).

Traffic and road parameters include speed, acceleration rate and grade parameters. For each lane of traffic, the SIDRA INTERSECTION software derives drive cycles consisting of a series of cruise, acceleration, deceleration and idling (stopped) time elements for specific traffic conditions represented by the intersection geometry, traffic control and demand flow rates based on data supplied by the user (see **Figure 1**). Thus, the drive cycles generated 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. The polynomial acceleration model used for estimating acceleration and deceleration times and distances is described in detail in Akçelik and Biggs (1987) and Akçelik and Besley (2001).

Fuel consumption and emission values are calculated for each of the four driving modes, and the results are added together for the entire driving manoeuvre from entry to the approach road at a point upstream of the intersection to a downstream point on the exit road. The model is applied to queued and unqueued 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 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 persons in vehicles. The cost model parameters include the 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. 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. **Table 1** gives the default cost model parameters for Australia, New Zealand and US (Akcelik and Associates 2006).

ROUNDABOUT METERING SIGNALS

There are many examples of roundabouts with unbalanced flow patterns in Australia, where part-time roundabout metering signals are used to create gaps in the circulating stream in order to solve the problem of excessive queuing and delays at approaches affected by highly directional flows (Akçelik 2003, 2004, 2005a, 2005b; Akçelik, Chung and Besley 1996, 1997). The use of metering signals is a cost-effective measure to avoid the need for a fully-signalized intersection treatment.

Roundabout metering signals are often installed on selected roundabout approaches and used on a part-time basis since they are required only when heavy demand conditions occur during peak periods. The Australian roundabout and traffic signal guides discuss the use of metering signals (Austroads 1993, 2003). The signalized roundabout solution has also been used extensively in the UK (e.g. Huddart (1983), Lines and Crabtree (1988), Shawaly, Li and Ashworth (1991), Hallworth (1992).

Figures 2 and 3 show typical arrangements for roundabout metering signals and an example from Melbourne, Australia (the case study used in this paper). The term **metered approach** is used for the approach stopped by red signals (approach causing problems for a downstream approach), and the term **controlling approach** is used for the approach with the queue detector, which is the approach helped by metering signals. When the queue on the controlling approach extends back to the queue detector, the signals on the metered approach display red (subject to signal timing constraints) so as to create a gap in the circulating flow. This helps the controlling approach traffic to enter the roundabout. When the red display is terminated on the metered approach, the roundabout reverts to normal operation.

Table 2 summarizes design and control parameters used for metering signals at various roundabouts in Melbourne, Australia. More detailed information about roundabout metering signals can be found in (Akçelik 2005b).

CASE STUDY

A revised version of the method described in (Akçelik 2005b) for the analysis of roundabout capacity and performance characteristics with metering signals is applied to the intersection of Nepean Highway and McDonald Street in Melbourne, Australia. In this case, the metered approach is McDonald Street and the controlling approach is Nepean Highway Southeast.

The following analysis method is used for modelling the effects of metering signals, which involve estimating operating characteristics for several traffic operation scenarios using SIDRA INTERSECTION.

(i) **No Metering Signals**: This is the **base case** which represents the normal roundabout operation without metering signals. The roundabout geometry and the am peak 30-min volumes (given as hourly flow rates) used in the analysis are shown in **Figure 4**.

The proportion of time RED signals can be displayed on the metered approach (McDonald St) depends on the degree of saturation of the metered approach under base case conditions. The proportion of time BLANK signals are displayed is calculated from $g / c = x_M / x_p$ and the proportion of time RED signals are displayed is calculated from $1 - g / c$, where g is the BLANK time, c is the cycle time (BLANK time plus RED time), x_M is the degree of saturation of the metered approach in Scenario (i) and x_p is the practical (target) degree of saturation. In this example, $x_M = 0.33$ (low value) and using $x_p = 0.85$, $g / c = 0.39$ is found. An approximate value of $g / c = 0.40$ is used (i.e. to display BLANK signals 40 per cent of the time and RED signals 60 per cent of the time).

(ii) **RED Signals on Metered Approach**: This represents roundabout operation with metering signals when the **metering signals display RED**, i.e. the metered approach (McDonald St) traffic is stopped and the rest of roundabout operates according to normal roundabout rules as shown in **Figure 5**. For this purpose, the metered approach is specified as a one-way exit road.

(iii) **BLANK Signals on Metered Approach**: This represents roundabout operation with metering signals when the **metering signals display BLANK signals** on the metered approach (McDonald St) following the display of the RED signals. The roundabout geometry specification is as in the base case. The flow rate from the metered approach is increased to the platooned departure flow rate due to the effect of queuing during red signals as shown in **Figure 6**. The platooned flow rate is the average flow rate crossing the signal stop line during the BLANK period, calculated from $q_d = q_a / (g / c)$, where g is the BLANK time and c is the cycle time (BLANK time plus RED time) and q_a is the arrival (demand) flow rate. The platooned flow rate for the metered approach in this case is determined using $g / c = 0.40$ as chosen in (i).

(iv) **AVERAGE Conditions for Non-Metered Approaches**: To determine the average operating conditions for Nepean Highway approaches (SE and NW), the results of RED Signals and BLANK Signals Scenarios (ii and iii) are combined to determine the **weighted average capacities** of these approaches using the proportions of time the RED and BLANK signals are displayed. Scenario (iv) is then created by emulating the weighted average capacities using the Environment Factor (calibration parameter) for Nepean Highway approaches.

(v) **SIGNAL ANALYSIS for Metered Approach**: This scenario is created to emulate the overall operation of **metered approach with metering signals** in order to determine the performance of the metered approach. The phases (red and blank) and timing information are shown in **Figure 7**. A cycle time of c = 120 s was chosen. The BLANK signals were displayed for 40 per cent of the time (g = 48 s) and RED signals were displayed for 60 per cent of the time (r = 72 s). The volumes are as in Scenario (i).

The saturation flow rates for the metered approach lanes (queue discharge rates during the BLANK signal phase) are specified as the capacity rates estimated for Scenario (iii). These are **960 veh/h for Lane 1** (shared left-turn and right-turn) and **870 veh/h for Lane 2** (right-turn only). These are converted to basic saturation flow rates by adjusting for turn adjustment factors. The flow ratesare as in Scenario (i), i.e. platooned arrival flow rates should not be used.

For estimating geometric delay, operating cost, fuel consumption and emissions, it is important that the intersection negotiation data (turn radius, negotiation speed and negotiation distance) for the metered approach in the signalized intersection scenario are specified to match the data used in the base conditions Scenario (i). This is because the geometry of the signalised intersection scenario is not a realistic representation of the roundabout geometry.

The capacity and performance results from this analysis, including annual sums, are presented in **Figures 8 and 9*.*** The hourly values were converted to annual values assuming 240 days per year (1 h per day) for the peak conditions. The results indicate that, as expected, metering signals reduce delay, queue length, fuel consumption, CO_2 emissions and operating cost on the controlling approach (Nepean Hwy SE) while increasing the corresponding values on the metered approach (McDonald St). The overall benefits that can be obtained from metering signals appear to be substantial. This implies a good benefit-cost ratio due to the low cost of implementing metering signals.

CONCLUDING REMARKS

The case study presented in this paper indicates substantial benefits from the implementation of roundabout metering signals in terms of operating cost, fuel consumption and pollutant emissions as well as delay and degree of saturation.

The instantaneous model used in SIDRA TRIP and the four-mode elemental model based on drive cycles (also called *modal* model) used in SIDRA INTERSECTION 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).

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Table 1: Default values of cost model parameters for Australia, New Zealand and US

Parameter	Australia	New Zealand	USA
***Cost Unit* (1)**	$ (AUD)	$ (NZD)	$ (USD)
Parameters for operating cost factor			
Pump price of fuel in "Cost Unit" per litre (or per gallon)	1.20 ($/L)	1.60 ($/L)	$ 0.65 ($/L) (2.40 $/gal)
Fuel resource cost factor	0.50	0.60	0.70
Running cost/fuel cost ratio	3.0	2.5	3.0
Parameters for time cost			
Average income (full time adult average hourly total earnings) in "Cost Unit" per hour	28.00 ($/h)	21.00 ($/h)	19.00 ($/h)
Time value factor as a proportion of average hourly income	0.60	0.60	0.40
Average occupancy in persons per vehicle	1.5	1.5	1.2
Vehicle parameters			
Light Vehicle Mass (average value in kg or lb)	1400	1400	1400 (3100 lb)
Heavy Vehicle Mass (average value in kg or lb)	11000	11000	11000 (24,000 lb)

Table 2 - Typical design and control parameters used for roundabout metering signals

Metered approach	
Signal stop-line setback distance	14 -24 m (46 - 79 ft)
Detector setback distance (if detector is used)	2.5 m (8 ft)
Loop length (if detector is used)	4.5 m (15 ft)
Minimum blank time setting	20 - 50 s
Maximum blank extension time settings	30 s
Blank signal gap setting	3.5 s
Yellow time	4.0 s
All-red time	1.0 - 2.0 s
Controlling approach	
Queue detector setback distance	50 - 120 m (164 - 394 ft)
Loop length for the queue detector	4.5 m (15 ft)
Minimum red time setting	10 - 20 s
Maximum red extension time settings	20 - 60 s
Queue detector gap setting	3.0 - 3.5 s
Queue detector occupancy setting: t_{oq}	4.0 - 5.0 s
Yellow time: t_{yR}	3.0 - 4.0 s
All-red time: t_{arR}	1.0 - 2.0 s

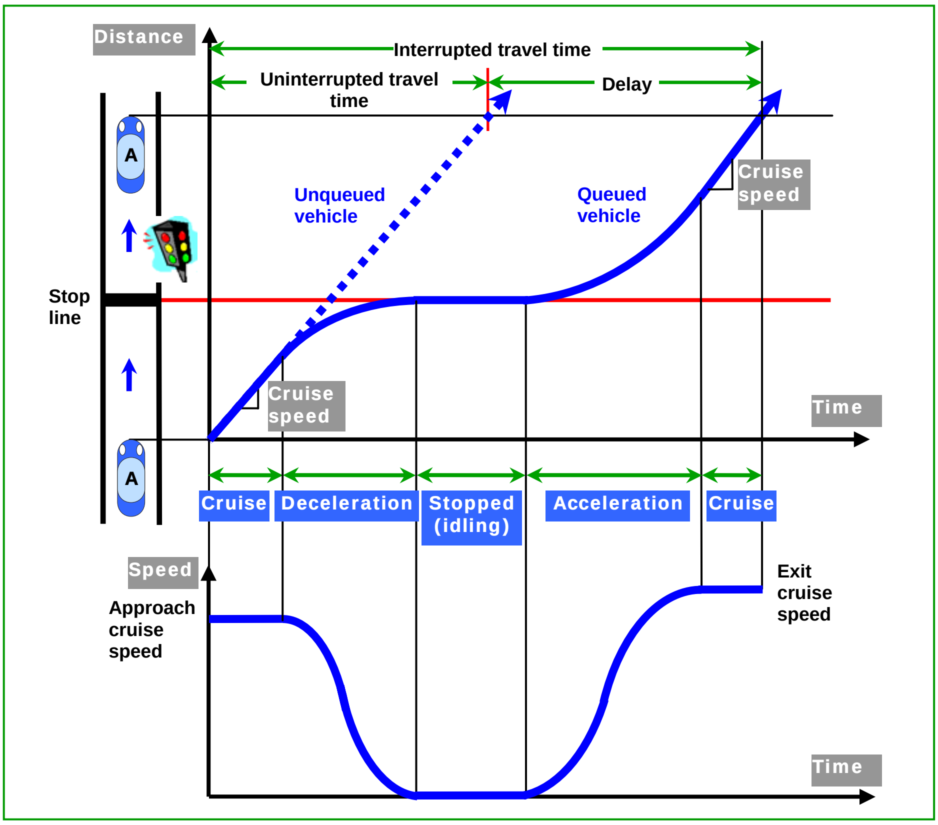

Figure 1: **Drive cycle during a stop at traffic signals (example)**

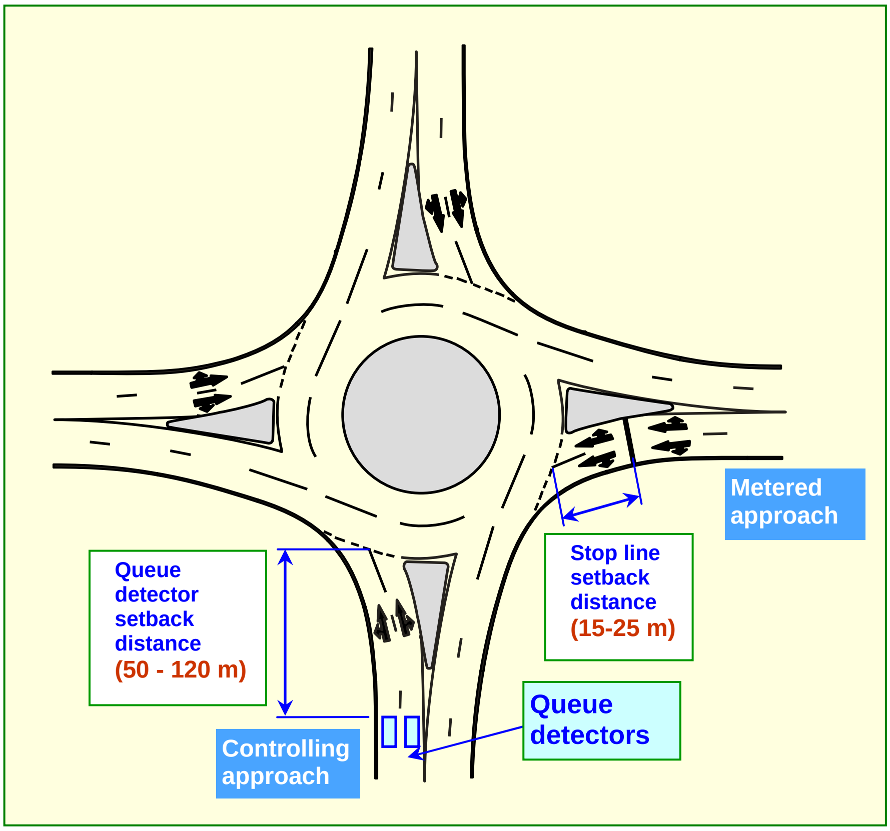

Figure 2: Typical arrangements for roundabout metering signals

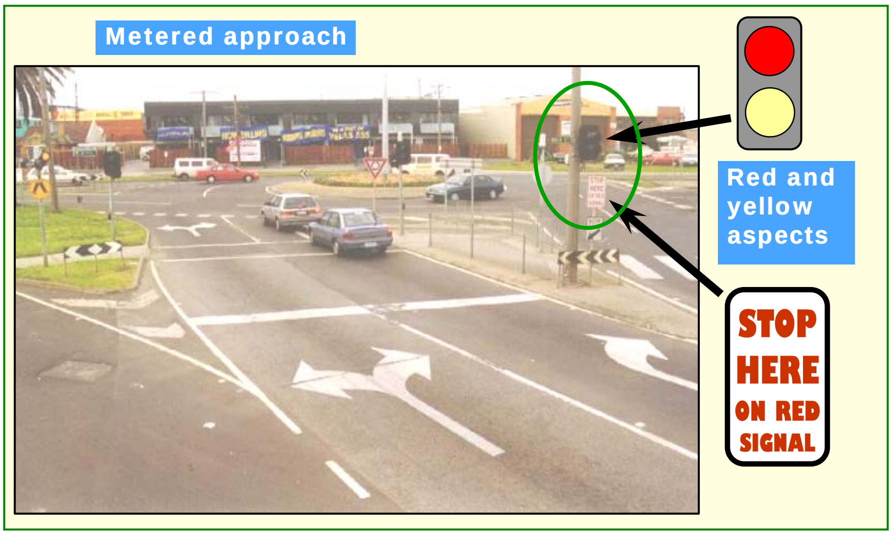

Figure 3: **A roundabout metering signals example from Melbourne, Australia (the case study presented in this paper)**

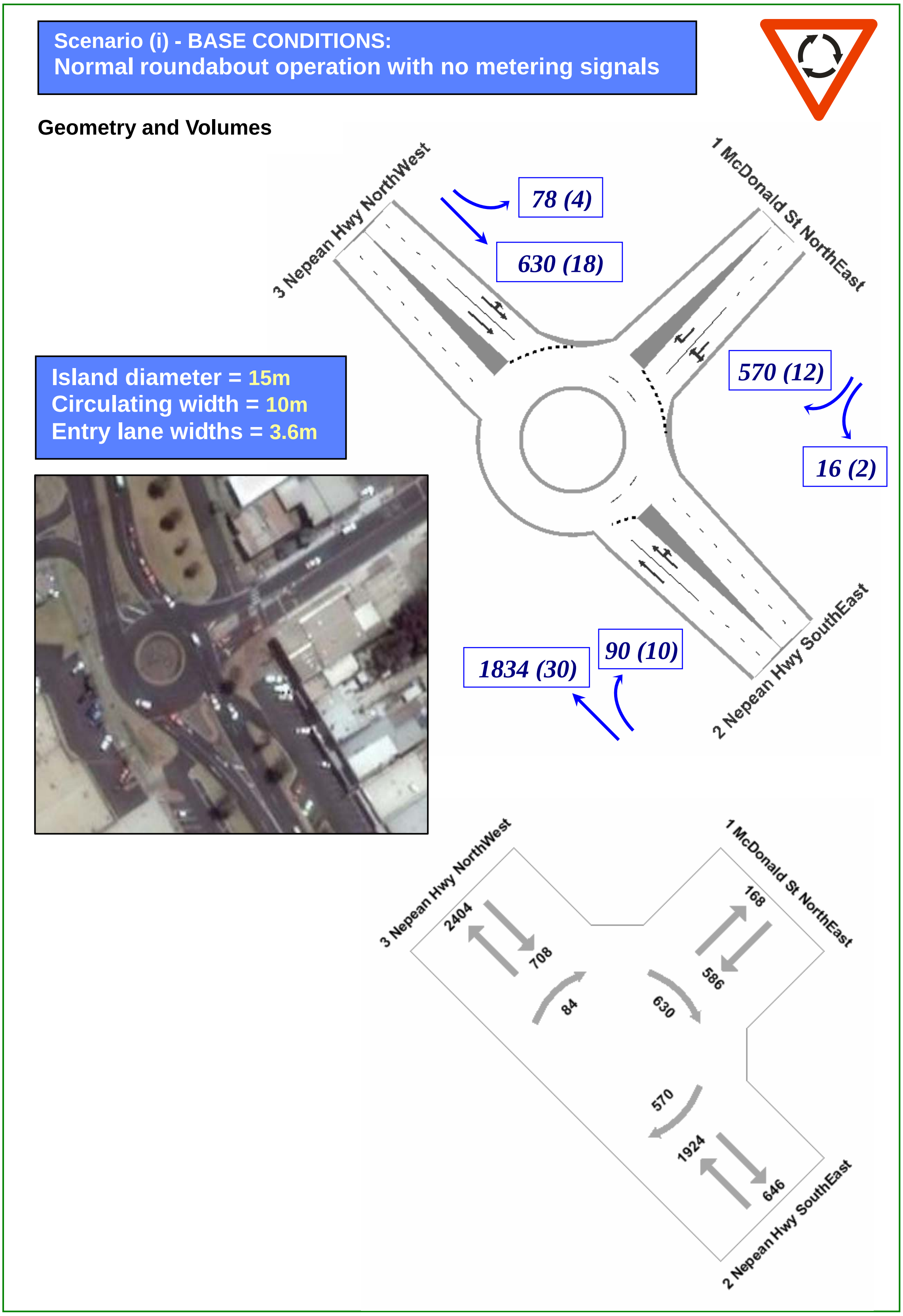

Figure 4: **Roundabout operating without metering signals (base condition)**

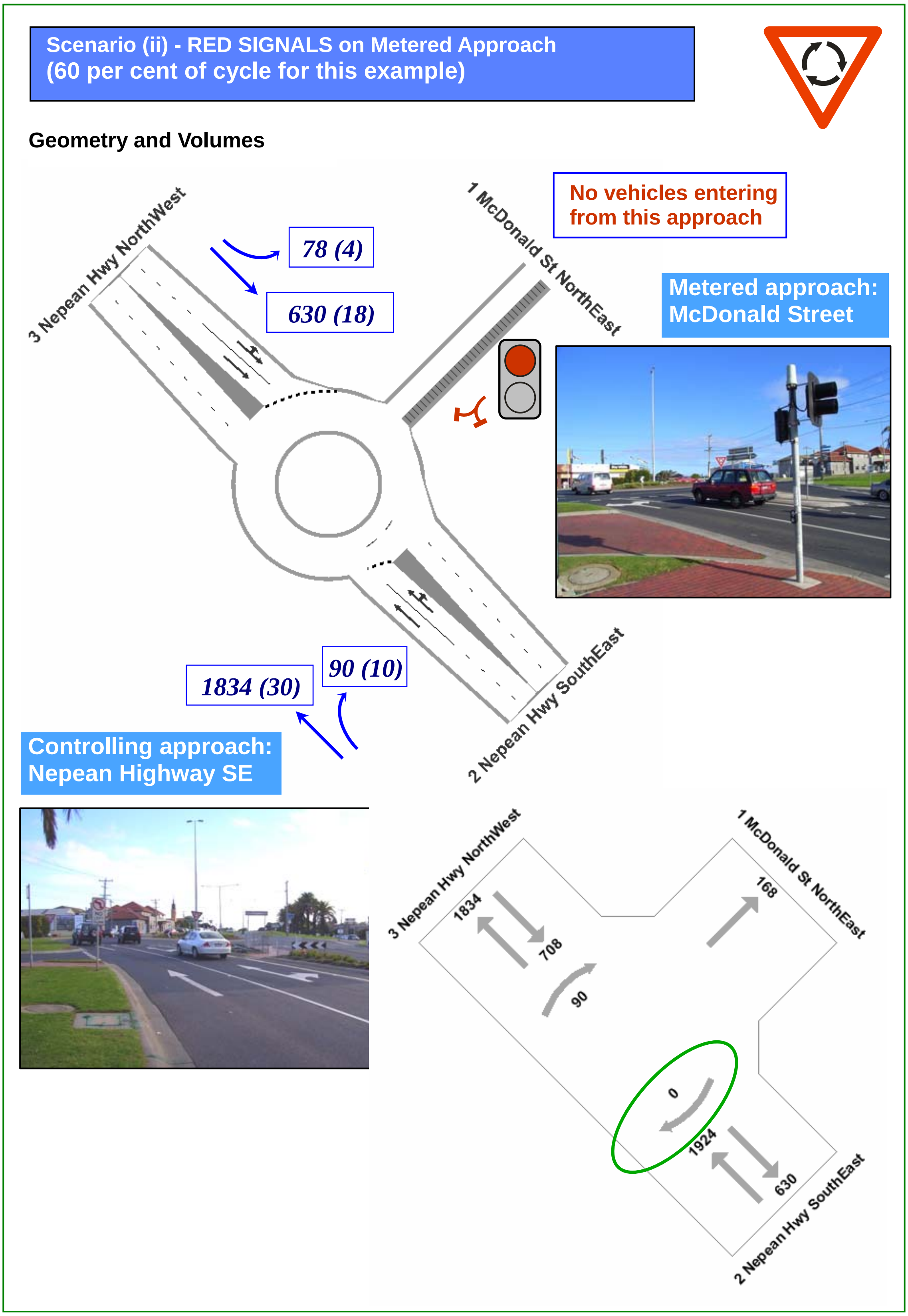

***Figure 5*: Roundabout operating with RED metering signals on the metered approach (McDonald St)**

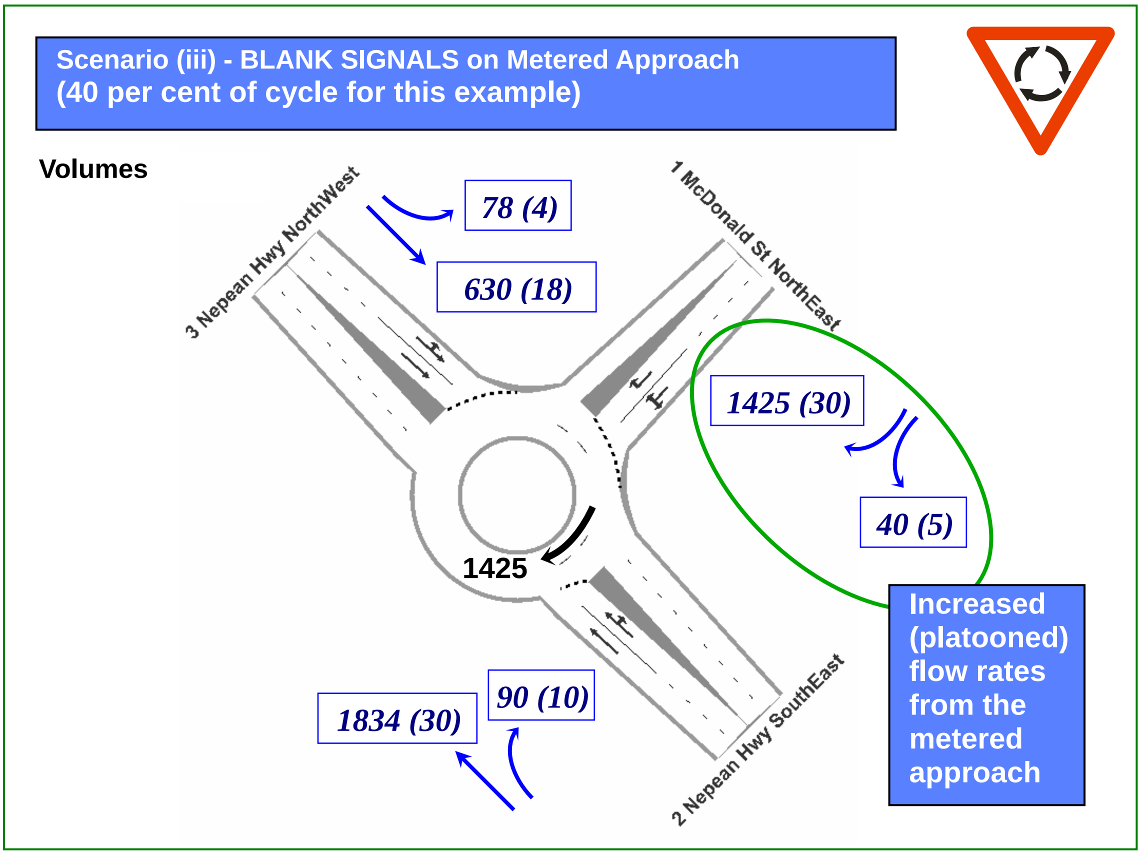

***Figure 6*: Roundabout operating with BLANK signals on the metered approach (McDonald St) - platooned flow rate entering from the metered approach**

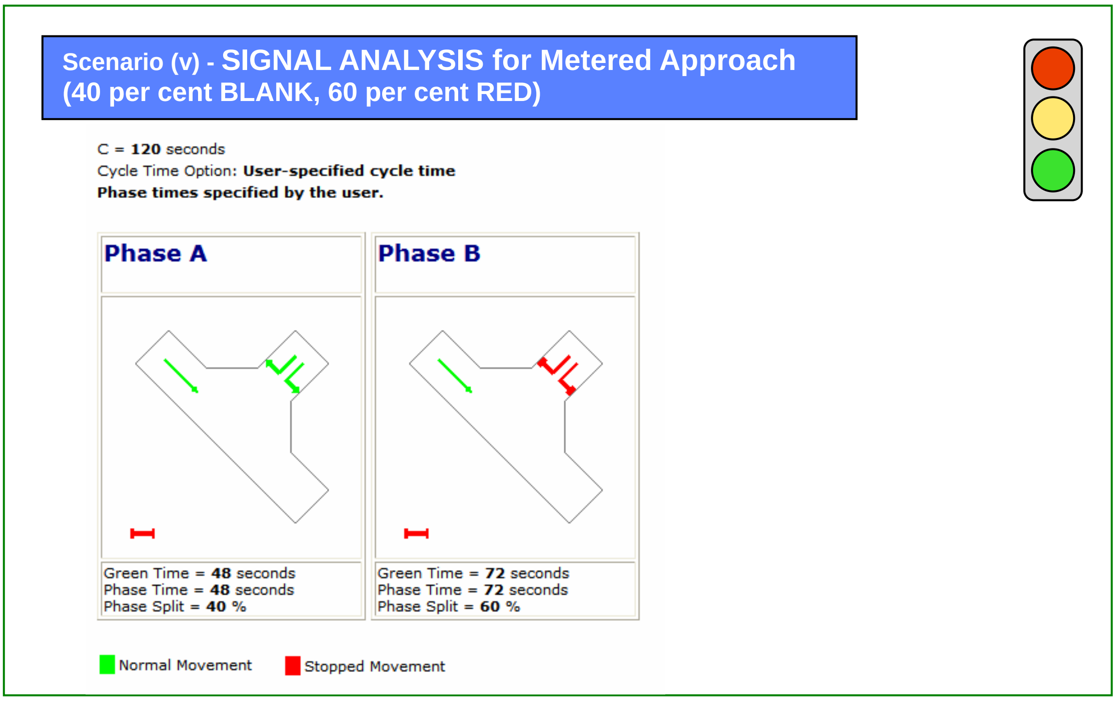

Figure 7: Metering signal timing analysis for the Nepean Highway - McDonald Street roundabout

No Metering Signals (Base case)

Hourly values

Leg	Description		Dem Flow	Cap	Deg of Satn	Aver Delay	95% Back of Queue	Eff. Stop Rate	Fuel Consumption	CO2 Emission	Oper. Cost
			(veh/h)	(veh/h)		(sec)	(m)		(L/h)	(kg/h)	($/h)
1	McDonald St (Leg 1)		586	1800	0.33	13.5	14.0	0.85	44.8	112.1	292.74
2	Nepean Hwy SE (Leg 2)		1924	1804	1.07	84.2	450.0	3.01	221.7	554.7	2075.17
3	Nepean Hwy NW (Leg 3)		708	2881	0.25	6.6	17.0	0.50	49.3	123.5	310.29
	Intersection		3218		1.07	54.3	450.0	2.06	315.80	790.30	2678.20

Annual values

Leg	Description	Days / Year	Dem Flow	Aver Delay	Worst App Delay	95% Back of Queue	Eff. Stop Rate	Total Stops	Fuel Consumption	CO2 Emission	Oper Cost
			(veh/y)	(sec)	(sec)	(m)		(veh/y)	(L/y)	(kg/y)	($/y)
	Intersection	240	772,320	54.3	84.2	450	2.06	1,594,402	75,792	189,672	642,768

With Metering Signals

Hourly values

Leg	Description		Dem Flow	Cap	Deg of Satn	Aver Delay	95% Back of Queue	Eff. Stop Rate	Fuel Consumption	CO2 Emission	Oper. Cost
			(veh/h)	(veh/h)		(sec)	(m)		(L/h)	(kg/h)	($/h)
1	McDonald St (Leg 1)		586	732	0.80	53.9	135.0	0.97	55.2	138.2	477.60
2	Nepean Hwy SE (Leg 2)		1924	2329	0.83	12.3	89.0	1.05	141.8	354.7	917.82
3	Nepean Hwy NW (Leg 3)		708	2987	0.24	6.6	16.0	0.50	49.3	123.5	310.20
	Intersection		3218		0.83	18.6	135.0	0.91	246.3	616.4	1705.62

Annual values

Leg	Description	Days / Year	Dem Flow	Aver Delay	Worst App Delay	95% Back of Queue	Eff. Stop Rate	Total Stops	Fuel Consumption	CO2 Emission	Oper Cost
			(veh/y)	(sec)	(sec)	(m)		(veh/y)	(L/y)	(kg/y)	($/y)
	Intersection	240	772,320	18.6	53.9	135	0.91	706,229	59,112	147,936	409,349

Nepean Hwy SE (Leg 2): Controlling approach; McDonald St (Leg 1): Metered approach

Figure 8: SIDRA INTERSECTION estimates of the performance of the Nepean Highway and McDonald St Roundabout with and without metering signals

Total per YEAR		Demand Flow	Average Delay	Worst Approach Delay	95% Back of Queue	Total Stops	Fuel Consumption	CO_2 Emission	Operating Cost
Option	Description	(veh/h)	(sec)	(sec/veh)	(m)	(veh/y)	(L/y)	(kg/y)	($/y)
1	No Metering Signals	772,320	54.3	84.2	450	1,594,402	75,792	189,672	642,768
2	With Metering Signals	772,320	18.6	53.9	135	706,229	59,112	147,936	409,349
	Difference	0	-36	-30	-315	-888,173	-16,680	-41,736	-233,419
	Per cent difference	0.0%	-65.7%	-36.0%	-70.0%	-55.7%	-22.0%	-22.0%	-36.3%

Figure 9: Benefits from metering signals for the Nepean Highway and McDonald St Roundabout