An Investigation of the Performance of Roundabouts with Metering Signals

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ABSTRACT

A major project was undertaken for VicRoads, the state transport authority in Victoria, to investigate the performance of roundabouts with metering signals in Melbourne, Australia. The research objectives included further development of analytical techniques to assess the performance of roundabouts with metering signals, and calibration and validation of these techniques for incorporation into the SIDRA INTERSECTION software. Twenty roundabouts with metering signals were considered as candidates for the project. Following site visits, five multi-lane roundabout sites were chosen for comprehensive surveys of traffic and driver behaviour at roundabouts with metering signals. The survey data included video recordings of driver gap acceptance behaviour, intersection turning movement volume counts, automated counting of circulating traffic, GPS-equipped floating car surveys, and metering signal timings. The peak 15-min intersection volumes at these sites were in the range 3268 to 5984 veh/h. Using the survey data, the entering and circulating traffic characteristics were investigated at the controlling and metered roundabout approaches. These included queue lengths, delays and queue spacing on approach roads, critical gap and follow-up headways of entering drivers, bunching and headway distribution of circulating traffic as well as circulating vehicle speeds. This paper presents various aspects of data collection, analysis, and findings of the project.

INTRODUCTION

The use of metering signals is a cost-effective measure to avoid the need for a fully-signalized intersection treatment when low capacity conditions occur during peak demand flow periods *(1-6)*, usually as a result of unbalanced flow patterns and high demand flow levels *(1-16)*. Roundabout metering signals are often installed on selected roundabout approaches and used usually on a part-time basis since they are required only when heavy demand conditions occur during peak periods. Metering signals have been used in Australia to alleviate the problem of excessive delay and queuing by creating gaps in the circulating stream. The Australian roundabout and traffic signal guides acknowledge the problem and discuss the use of metering signals *(17,18)*.

The basic principles of the operation of roundabout metering signals have been explained and case studies have been presented in previous papers by the author (*1,2,5*). These case studies included one-lane, two-lane and three-lane roundabouts from Australia, UK and the USA with total intersection flow rates in the range 1700 to 5300 veh/h. The analyses were carried out using the SIDRA INTERSECTION micro-analytical software package *(19)*.

A method developed by the author (unpublished) for incorporation into SIDRA INTERSECTION was used by Natalizio *(4)* to establish the conditions in which benefits from metering signals may be achieved.

A major project was undertaken for VicRoads, the state transport authority in Victoria, to investigate the performance of roundabouts with metering signals in Melbourne, Australia. The research objectives included further development of analytical techniques to assess the performance of roundabouts with metering signals, and calibration and validation of these techniques for incorporation into the SIDRA INTERSECTION software. One of the aims of the project was an assessment of driver behaviour at roundabouts with metering signals compared with the behaviour at unmetered roundabouts.

Twenty roundabouts with metering signals were considered as candidates for the project. Following site visits, five multi-lane roundabout sites were chosen for comprehensive surveys of traffic and driver behaviour at roundabouts with metering signals.

Using the survey data, the circulating and entering traffic characteristics were investigated at the controlling and metered roundabout approaches. These included critical gap and follow-up headways of vehicles in entry lanes, proportion of free (unbunched) vehicles and speeds in circulating traffic, and queue lengths, delays and average queue spacings for traffic queued in entry lanes. Various aspects of data collection, analysis, and findings of the project are presented in the following sections.

SURVEYS

Surveys of traffic and driver behaviour at roundabouts with metering signals were conducted at five major multi-lane roundabout sites in July 2006. At the selected sites, the metering signals were operated only by the detection of queue length on the controlling approach, and not by special vehicles (trams, buses, trains) or pedestrians. Sites with these features in the initial set of 20 roundabouts were excluded from further consideration.

The term *metered approach* is used for the signalised approach, which is the approach causing the problems for a downstream approach. The term *controlling approach* is used for the approach with the queue detector, which is the approach benefited by metering signals.

The sites were selected so as to cover a wide range of:

- unbalanced flow conditions (to include both through and turning dominant movements),
- roundabout size and configuration (3 and 4 approaches, 2 and 3 circulating lanes),
- surrounding land-use and density (retail, industrial, residential), and
- proportion of heavy vehicles.

Data collected during these surveys included:

- intersection turning movement volume counts by a team of observers (manual),
- video recordings of driver gap acceptance behaviour on metered and controlling approaches,
- headways and speeds of circulating traffic in front of metered and controlling approaches recorded using automatic traffic counter - classifier units,
- travel data collected using two floating cars with GPS units which recorded the position and speed at one-second intervals (driven repeatedly through the roundabout alternating between the metered and controlling approaches), and
- signal timings (observed as well as SCATS control system information).

All these surveys were carried out simultaneously for each site. The layout plan was available for each roundabout.

Five survey sites selected at four roundabouts are shown in *Table 1* and *Figures 1 to 5* (including SIDRA INTERSECTION layout diagrams to show lane details, and photos of metered and controlling approaches at each roundabout). Intersection 2816 has two separate sets of metering signals, activated separately for the morning and afternoon peak periods. Both peak periods were surveyed at this site, whereas only one peak period was surveyed at the other three sites, giving a total of 5 surveys.

Surveys conducted in the morning peak period commenced at 7.00 am, roughly 30 minutes before sunrise, and finished at 9.00 am. Surveys conducted in the afternoon peak period started at 3.30 pm when there was significant school traffic present, or at 4.00 pm otherwise; and finished at 6.00 pm, roughly 30 minutes after sunset.

The survey data were used to characterize the circulating and entering traffic at the controlling and metered approaches of the roundabouts, including queue lengths, delays and queue spacing on approach roads, critical gap and follow-up headways of entering drivers, bunching and headway distribution of circulating traffic as well as circulating vehicle speeds. The results are summarised in the following sections.

Table 1 Roundabout survey sites

Date and Time of Survey	Metered Approach	Controlling Approach	Number of Circulating Lanes	Central Island Diameter	Total 15-min Peak Volume as Hourly Rate
2169: Mickleham Road - Broadmeadows Road Deviation, Tullamarine					
Thursday, 6 Jul 2006, 7.00 am - 9.00 am	Mickleham Road (South)	Mickleham Road (North)	1 / 2	50 m (164 ft)	3268 veh/h (8.20 - 8.35 am)
In the am peak period, traffic exiting from the Tullamarine Freeway travels North along Mickleham Rd turning right onto Broadmeadows Rd Deviation. This movement is in a single lane and opposes a large volume of traffic heading South towards the city. There is little traffic on Broadmeadows Rd Deviation turning right to head North along Mickleham Rd, therefore there is little interruption to traffic from Mickleham Rd South. Metering signals on the Mickleham Rd South approach are used to limit queue length and delay on Mickleham Rd North. An analysis of metering signals at this roundabout was reported by the author *(4)*. The current traffic flow pattern and demand flow levels differ from those specified in the AUSTROADS 1993 Roundabout Guide *(17)*. Under the current conditions, metering signals on Mickleham Rd South approach were activated only occasionally.					
2816: Greensborough Bypass - Diamond Creek Road, Greensborough					
Tuesday, 11 Jul 2006, 7.00 am - 9.00 am	Civic Drive	Diamond Creek Road (Northeast)	2 / 3	71 m (233 ft)	4568 veh/h (7.50 - 8.05 am)
Tuesday, 11 Jul 2006, 3.30 pm - 6.00 pm	Diamond Creek Road (Southeast)	Greensborough Bypass	2 / 3	71 m (233 ft)	5984 veh/h (5.25 - 5.40 pm)
At this large roundabout, separate metering conditions are provided for the am and pm peak periods. In the **am peak period**, there is a heavy movement on the Diamond Creek Rd Northeast approach (towards the city and the Western Ring Rd). Relatively lower traffic flow from Greensborough Bypass does not provide adequate gaps for traffic on the Diamond Creek Rd Northeast approach by interrupting the Civic Drive traffic sufficiently. Metering signals on Civic Drive are used to limit queue length and delay on the Northeast approach of Diamond Creek Rd. In the **pm peak period**, Greensborough Bypass carries a heavy movement. Relatively lower traffic flow from Diamond Creek Rd Northeast does not provide adequate gaps for traffic on the Greensborough Bypass approach by interrupting the Diamond Creek Rd Southeast traffic sufficiently. Metering signals on the Diamond Creek Rd Southeast approach are used to limit queue length and delay on Greensborough Bypass.					
3715: Boundary Road - Governor Road, Braeside					
Tuesday, 18 Jul 2006, 7.00 am - 9.00 am	Governor Road (East)	Boundary Road (South)	2 / 3	39 m (128 ft)	5296 veh/h (8.10 - 8.25 am)
At this roundabout which is in an industrial area, Boundary Rd South approach carries heavy traffic in the am peak period. Relatively lower Southbound traffic flow from Boundary Rd does not provide adequate gaps for traffic on Boundary Rd South approach by interrupting the Governor Rd East traffic sufficiently. Metering signals on Governor Rd East are used to limit queue length and delay on the South approach of Boundary Rd.					
974: South Gippsland Highway - Pound Road, Hampton Park					
Tuesday, 18 Jul 2006, 4.00 pm - 6.00 pm	South Gippsland Highway (South)	South Gippsland Highway (North)	2	49 m (161 ft)	3940 veh/h (4.35 - 4.50 pm)
This roundabout is in a low urban density area, with negligible traffic on Pound Rd West approach. A significant "450-degree" turn was observed on South Gippsland Highway North approach (turning right into the roundabout, then exiting to Pound Rd East rather than turning left to Pound Rd East). In the pm peak period, traffic turning right from the South Gippsland Highway South approach, heading towards Pound Rd East (and the South Gippsland Freeway), interrupts heavy traffic from South Gippsland Highway North approach. Relatively lower traffic flow from Pound Rd East does not provide adequate gaps for traffic on South Gippsland Highway North approach by interrupting the South Gippsland Highway South traffic sufficiently. Metering signals on the South approach of the South Gippsland Highway are used to limit queue length and delay on the North approach of the South Gippsland Highway.					

Drive rule: Left-hand side of the road

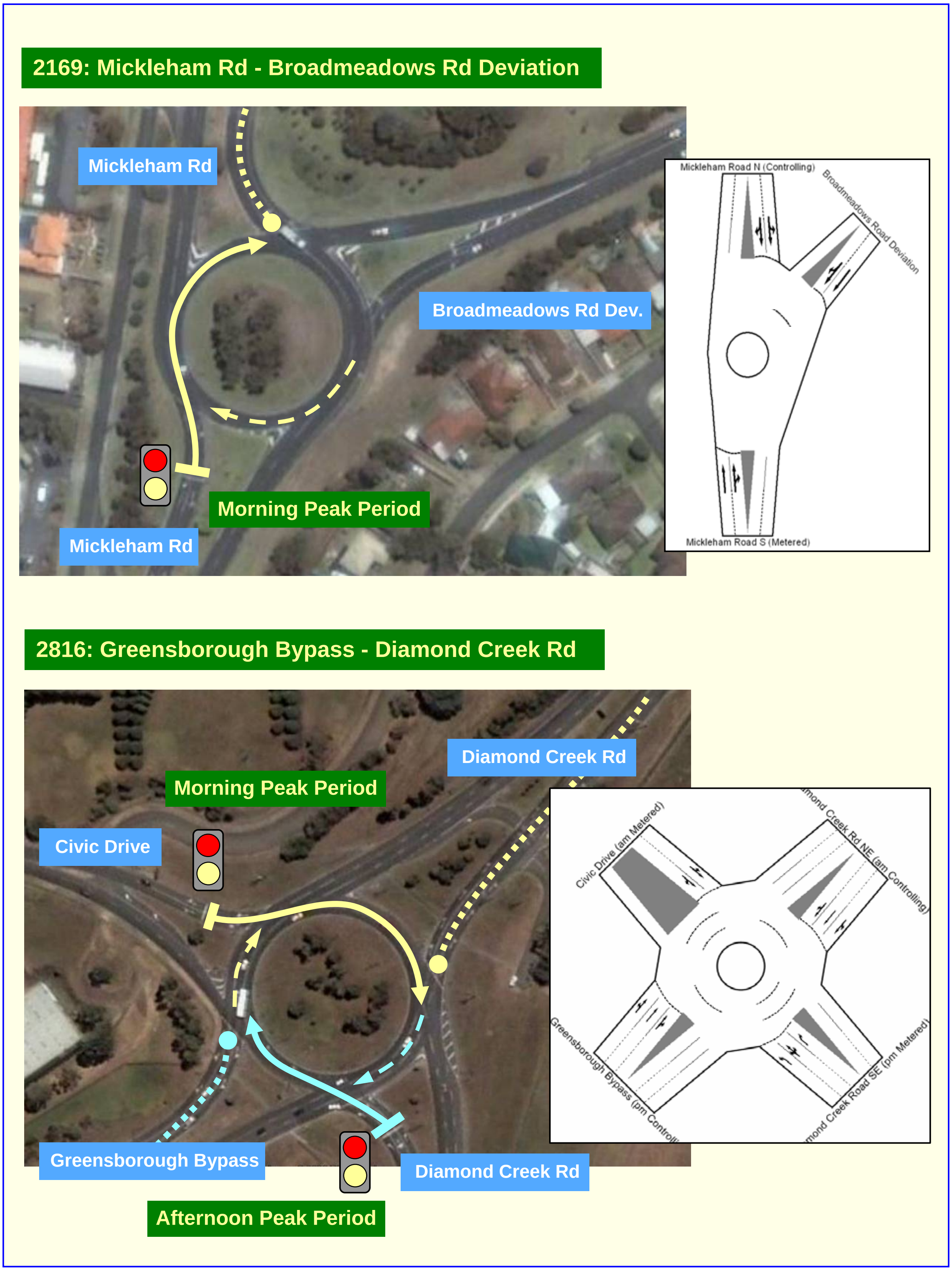

Figure 1 - Roundabout survey sites
(drive rule: left-hand side of the road)

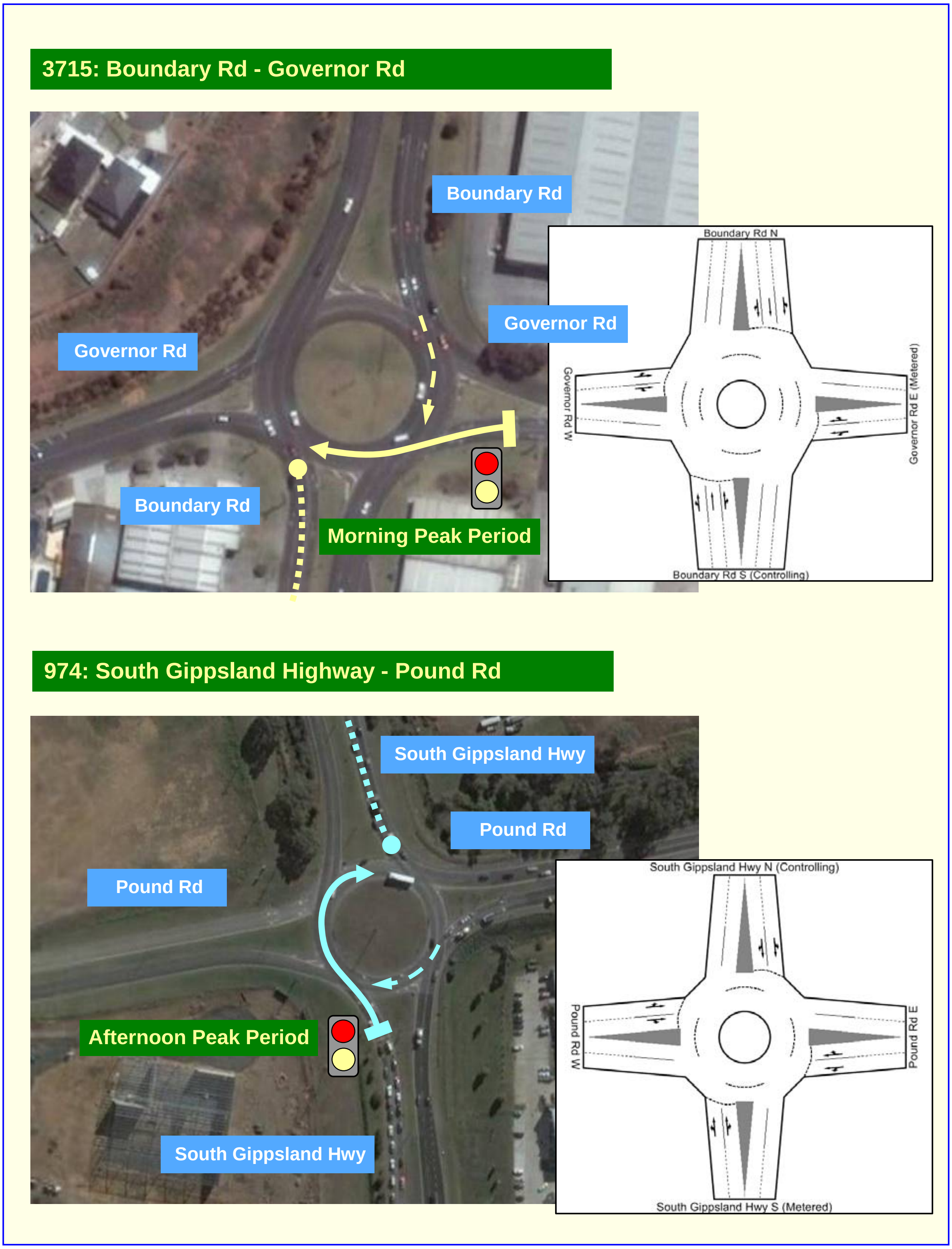

Figure 2 - Roundabout survey sites
(drive rule: left-hand side of the road)

Figure 3 - Survey sites photos
(drive rule: left-hand side of the road)

Metering Signal Timing

The metering signal timings were recorded by the VicRoads SCATS control system and verified against a sample of the times observed in the field. The averages and standard deviations of the cycle time (sum of blank and red phase times), yellow time, red time and percentage red are shown in *Table 2*. It was not possible to obtain data for the Mickleham Road - Broadmeadows Road Deviation site on the survey day but it was noted that the metering signals were rarely operational at this site (however, traffic data for this site are included in the analyses). The data supplied for the afternoon peak period at Greensborough Bypass - Diamond Creek Road did not contain the yellow and red time information.

Table 2 Measured roundabout metering signal timing

Site	Cycle Time (s)	Yellow Time (s)	Red Time (s)	Percentage Red
Mickleham Road - Broadmeadows Rd Deviation	n/a	n/a	n/a	n/a
Greensborough Bypass - Diamond Creek Rd (Morning)	100.0 ± 15.0	3.7 ± 0.6	30.7 ± 0.6	31% ± 2%
Greensborough Bypass - Diamond Creek Rd (Afternoon)	114.0 ± 5.0	n/a	n/a	n/a
Boundary Rd - Governor Rd	154.0 ± 32.0	4.0 ± 0.0	73.1 ± 6.6	47% ± 11%
South Gippsland Hwy - Pound Rd	80.0 ± 2.0	3.0 ± 0.0	58.6 ± 3.1	73% ± 4%

Values shown are mean ± standard deviation.

Figure 4 - Survey sites photos
(drive rule: left-hand side of the road)

Figure 5 - Survey sites photos
(drive rule: left-hand side of the road)

CHARACTERISTICS OF ENTERING TRAFFIC

Queue Length and Delay

The travel data from floating car surveys were used to estimate queue lengths and delays to traffic using the roundabout on metered and controlling approaches. These were based on the travel distance and time from the instant when the vehicle speed dropped below 25 km/h (16 mph) until it reached the give-way (yield) line. *Figure 6* shows an example of a floating car survey result in which the vehicle reaches the back of the queue 187 s, or 430 m (1410 ft), before crossing the roundabout give-way (yield) line on a controlling approach.

Approach delays were calculated by subtracting the time taken to cover the queue length at free-flow speed from the measured time-in-queue. Departure delays were calculated from the time and distance taken to accelerate to the free-flow speed. *Table 3* shows the queue length (distance) and delay results from the floating car survey. The five survey sites can be seen to encompass a wide range of operating conditions, ranging from low congestion to long delays and queues.

To date, the SIDRA INTERSECTION software has been shown to estimate the effect of unbalanced flow conditions reliably (*(1-3,5-8)*). This applied to the survey sites studied in this project in general terms. However, at a more detailed level, the base case analyses of controlling approaches and the analyses of metered approaches indicated that delay and queue length were underestimated in some cases. An important factor in this was the underestimation of demand volumes at oversaturated approaches as a result of the use of turning movement volumes counted at the give-way (yield) lines rather than demand volumes measured beyond the back of queues.

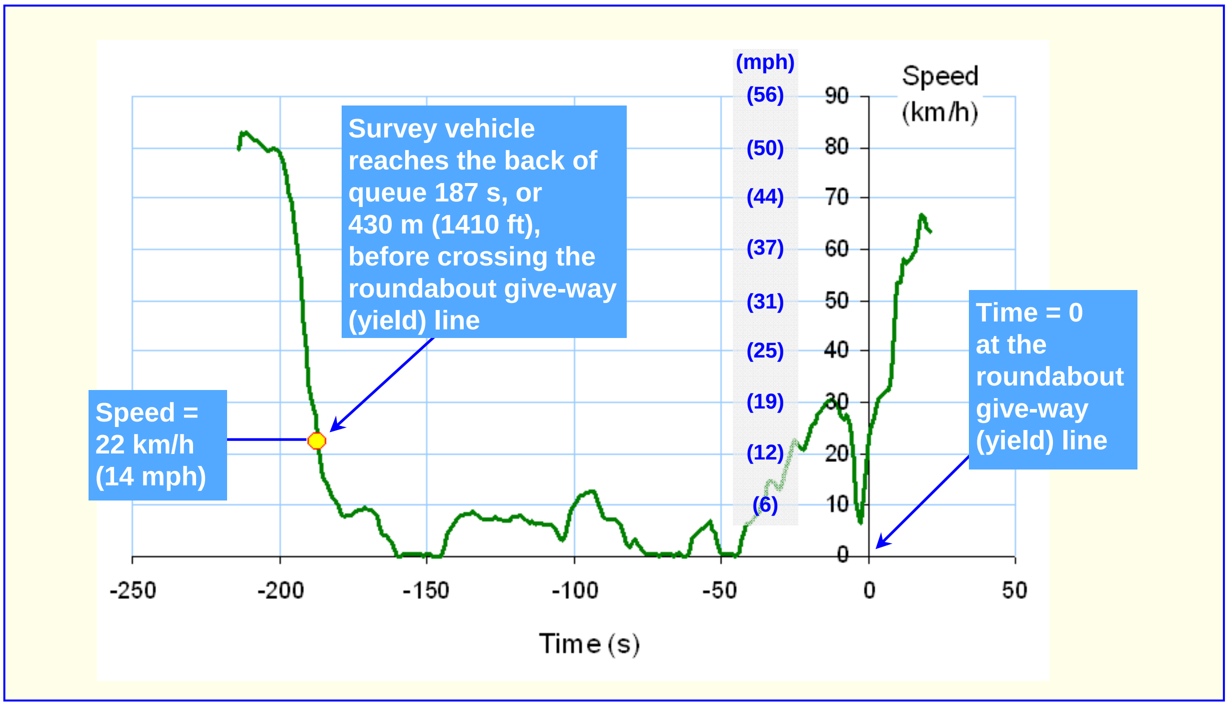

Figure 6 - Example speed profile of a vehicle at a roundabout approach: Boundary Road Northbound (controlling) approach at Boundary Road - Governor Road

Table 3 Queue length and delay results measured from the GPS floating car survey

Site	Approach	Number of Runs	Average Queue Length (m)	Average Time in Queue (s)	Average Approach Delay (s)	Average Departure Delay (s)
Mickleham Rd - Broadmeadows Rd Deviation	Controlling	27	23	6	5	7
	Metered	28	7	2	1	3
Greensborough Bypass - Diamond Creek Rd (Morning)	Controlling	31	101	37	32	6
	Metered	30	41	40	37	7
Greensborough Bypass - Diamond Creek Rd (Afternoon)	Controlling	21	100	29	24	10
	Metered	29	95	103	97	17
Boundary Rd - Governor Rd	Controlling	25	366	119	100	9
	Metered	23	143	72	64	4
South Gippsland Hwy - Pound Rd	Controlling	15	619	181	153	9
	Metered	14	320	377	362	9

To account for the underestimation of demand volumes, additional SIDRA INTERSECTION analyses were conducted using a 15% higher controlling approach volume than that recorded during the turning movement surveys. This gave delays and queue lengths closer to the observed values. This is an important issue to be taken into account in the design of improvements to roundabouts with oversaturated approaches. Without using true demand flows, benefits from metering signals and other intersection improvements will be underestimated, and when implemented, the design may be inadequate in coping with true demand volumes.

Queued Vehicle Spacing

The average queued vehicle spacing per vehicle (jam spacing) was estimated from the results of the floating car survey and video recordings of the front of the queue. SIDRA INTERSECTION uses this parameter to convert the queue length in vehicles to queue length in metres. Thus it is important to have an accurate estimate of this parameter in order to estimate the extent of the back of queue.

The floating car survey gives the times that a GPS-equipped car reaches the back of the queue and the front of the queue, as well as the queue length (distance). The video recordings were used to count the number of vehicles leaving the front of the queue (in the same lane as the floating car) in the time taken by the floating car to travel from the back to the front of the queue. The average queued vehicle spacing per vehicle was estimated by dividing the queue length by the number of vehicles in the queue.

The average queue spacing values determined using this method plotted against the average speed that the floating car moved through the queue implied an average jam spacing of 9.8 m (32 ft) for light vehicles. For this purpose, a heavy vehicle factor of 2.0 was used and data points with spacing greater than 20 m were eliminated.

Akçelik, Besley and Roper *(20)* reported jam spacings of light vehicles in queues at signalised intersections in the range of 5.9 to 7.3 m (19 to 24 ft). SIDRA INTERSECTION uses a default value of 7 m (23 ft) for a light vehicle and 13 m (43 ft) for a heavy vehicle for the standard left-hand version, and 7.6 m (25 ft) for a light vehicle and 14 m (46 ft) for a heavy vehicle for the US version *(19)*. Also see Long *(21)*. The larger jam spacing obtained in this study for roundabouts may be due to the continual flow discharge possible from the front of the moving queue. This would indicate that the same number of vehicles queued on a roundabout approach would extend further back compared with a signalised intersection.

Critical Gap and Follow-up Headway Values

Driver gap acceptance data were extracted by analysing the video recordings made of the behaviour of drivers entering the circulating road at both the controlling and metered approaches of each roundabout during the peak hour. Times at which circulating traffic crossed the detector tubes (roughly perpendicular to the end of the splitter island) were also recorded, as were the lanes and vehicle types of all vehicles.

Siegloch's method *(22)*, as described in TRB *(23)*, Brilon, Koenig and Troutbeck *(24)* and Akçelik *(25)*, was used to estimate the critical gap and follow-up headway parameters from this data. This relatively simple method requires queued conditions of the entry (minor) stream since the critical gap and follow-up headway parameters are relevant to capacity estimation. The method was applied for each 15-minute period at each lane of each approach for all five sites, giving a total of 90 estimates of critical gap and follow-up headway. The circulating flow rate was estimated from the number of circulating vehicles in each 15-minute period.

Table 4 shows the statistics for critical gap (headway time) and follow-up headway values measured at five survey sites, as well as the values estimated using the method employed in SIDRA INTERSECTION *(7,17,19,26, 27)*. Circulating flow rates, entry lane flow rates and proportions of heavy vehicles are also shown.

Troutbeck *(27)* distinguished between the gap acceptance behaviour of the *dominant* and *subdominant* lanes at a roundabout approach. The dominant lane at a multi-lane roundabout approach is identified as the lane with the largest volume. The gap-acceptance model used in SIDRA INTERSECTION makes use of this distinction. The critical gap and follow-up headway values measured at the survey sites showed little evidence of difference in critical gap and follow-up headway values of dominant and subdominant lanes.

Figure 7 shows the measured critical gap and follow-up headway values for controlling and metered approaches. The trend lines indicate little difference in critical gap values between controlling and metered approaches, but indicate different trends for follow-up headway values. In *Figure 7*, the follow-up headway values at lower circulating flow rates at controlling approaches are seen to be smaller than those at metered approaches. The average values of critical gap and follow-up headway for controlling and metered approaches are very close, and the trend lines are affected by a large number of points occurring at high circulating flows at metered approaches without corresponding points for controlling approaches. However, it is possible that queued vehicles on a controlling approach waiting for the metered approach traffic to be stopped will depart quickly when longer gaps occur in the circulating traffic.

Table 4 Measured and estimated critical gap and follow-up headway values

	Circulating Traffic		Entry Lane Traffic		Measured		Estimated	
	Flow Rate (veh/h)	Heavy Vehicles	Flow Rate (veh/h)	Heavy Vehicles	Critical Gap (s)	Follow-up Headway (s)	Critical Gap (s)	Follow-up Headway (s)
Metered and controlling approaches together								
Minimum	134	0.0%	174	0.0%	2.13	1.44	2.17	1.43
15th percentile	356	1.1%	288	0.7%	2.79	2.02	2.54	1.84
Mean	674	4.6%	677	3.4%	3.20	2.30	3.37	2.10
85th percentile	984	8.6%	985	6.7%	3.60	2.59	3.98	2.38
Maximum	1365	14.5%	1130	12.5%	4.31	3.25	4.83	3.11
Metered approaches only								
Minimum	134	0.0%	174	0.0%	2.47	1.76	2.17	1.75
15th percentile	175	2.0%	238	0.0%	2.77	2.18	2.55	1.93
Mean	794	5.1%	352	4.6%	3.15	2.39	3.30	2.25
85th percentile	1131	8.5%	438	7.6%	3.60	2.63	3.97	2.53
Maximum	1365	12.6%	739	12.5%	3.92	3.25	4.83	3.11
Controlling approaches only								
Minimum	229	0.0%	666	0.4%	2.13	1.44	2.21	1.43
15th percentile	379	0.8%	803	1.1%	2.79	2.01	2.57	1.58
Mean	597	4.3%	910	2.6%	3.21	2.26	3.43	1.99
85th percentile	829	8.6%	1015	3.8%	3.59	2.55	4.05	2.26
Maximum	961	14.5%	1130	6.1%	4.31	2.82	4.63	2.41

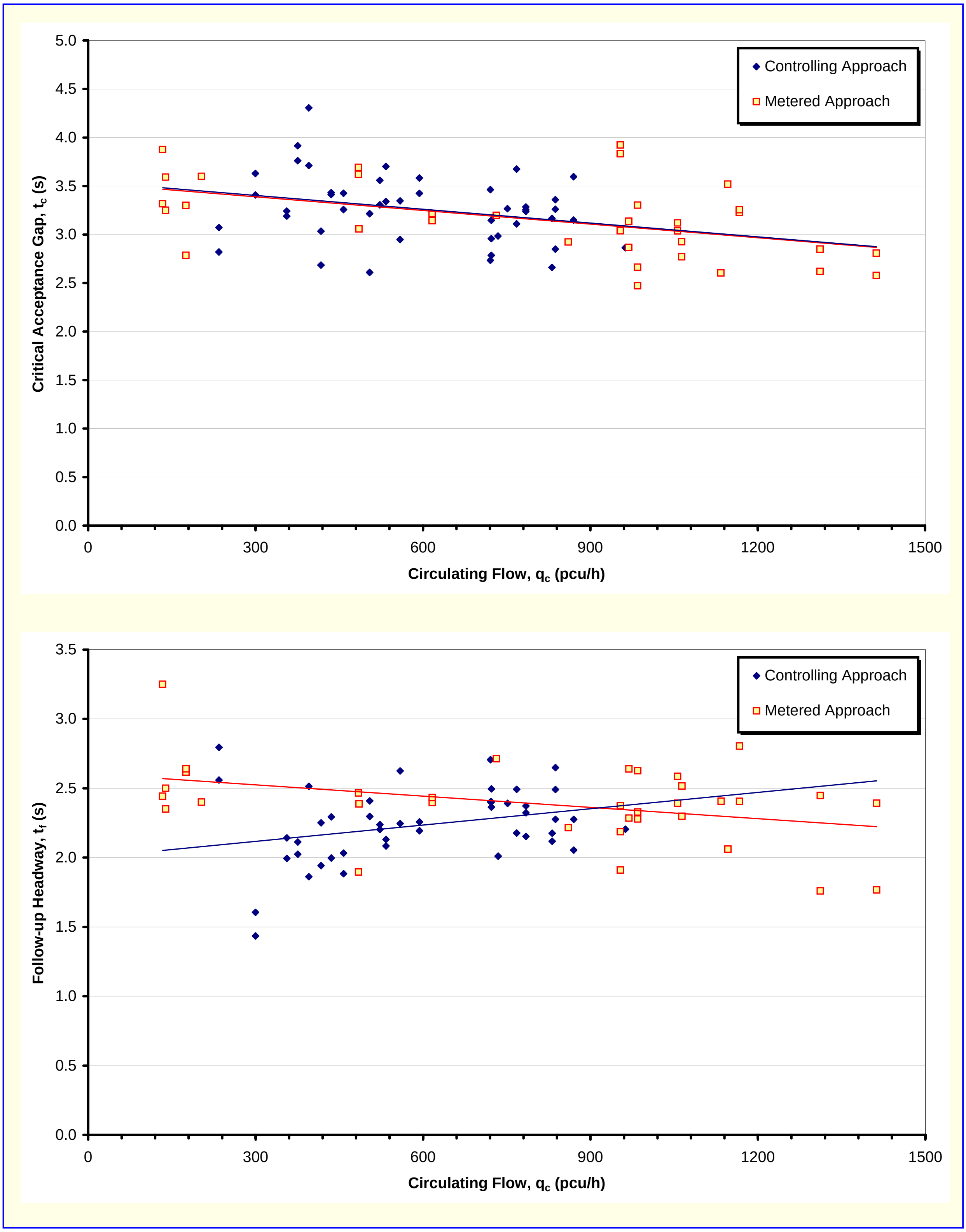

Figure 7 - Measured critical gap and follow-up headway values for controlling and metered approaches

CHARACTERISTICS OF CIRCULATING TRAFFIC

Bunching and Headway Distribution

The SIDRA INTERSECTION software uses the bunched exponential distribution of headways to model the circulation traffic. This model uses relationship between the proportion of free (unbunched) vehicles and the circulating flow rate. SIDRA INTERSECTION employs a relationship that uses the delay parameter of "Akçelik's" speed - flow model as a bunching parameter, thus linking the bunching and speed - flow models, representing in-stream vehicle interactions and resulting queuing in terms of traffic bunching characteristics *(28)*.

For estimating the parameters of the model of the proportion of free (unbunched) vehicles, data from all single-lane sites were combined, as were all data for the two-lane and three-lane sites. The survey data did not indicate a significant difference between metered and controlling approaches in terms of the proportion of free vehicles.

The survey data and calibrated models indicated higher proportions of free vehicles (less bunching) for a given circulating flow rate than the data reported by Troutbeck *(27)*. The calibrated models indicated satisfactory estimation of circulating stream headway distributions.

There is some difficulty about the nature of the differences between the survey data and the data reported earlier, i.e. whether these findings are specific to roundabouts with metering signals, or to all roundabouts generally. However, based on the survey data, it does not appear to be possible to attribute the higher levels of proportion free at the survey sites to the effect of metering signals.

Negotiation Speeds

Speeds of the circulating vehicles (*negotiation speeds*) recorded by the automatic traffic counters during the peak hour were examined for traffic in front of the metered and controlling approaches. The negotiation speeds depend on the composition of the circulating traffic, with turning vehicles generally having lower negotiation speeds than vehicles going straight through the roundabout. The average negotiation speeds were in the range 29.5 to 38.3 km/h (18.3 to 23.8 mph), increasing with the diameter of the roundabout as expected.

CONCLUDING REMARKS

The analyses of data collected at five roundabout sites during this project have indicated that while there is little difference between critical gap values for controlling and metered approaches, the follow-up headway values at lower circulating flow rates at controlling approaches are smaller than those at metered approaches. The average values of critical gap and follow-up headway for controlling and metered approaches are very close, and the trend lines are affected by a large number of points occurring at high circulating flows at metered approaches without corresponding points for controlling approaches. However, it is possible that queued vehicles on a controlling approach waiting for the metered approach traffic to be stopped will depart quickly when longer gaps occur in the circulating traffic.

The critical gap and follow-up headway values measured at the survey sites showed negligible difference in these entry traffic gap-acceptance parameters between dominant and subdominant lanes. This finding differs from the earlier research findings of Troutbeck *(27)* based on data collected on Australian roundabouts more than 20 years ago.

Survey data also indicated higher proportion of free (lower proportion of bunched) vehicles for circulating traffic compared with the models based on data reported by Troutbeck *(27)*. The method used in this project for calibrating the proportion of free vehicles differed from the method used by

Troutbeck *(27)*. However, based on the survey data, it did not appear to be possible to attribute the higher levels of proportion free at the survey sites to the effect of metering signals.

Further research is recommended to establish whether these findings are specific to relatively large roundabouts with metering signals, or to all roundabouts generally (e.g. because driver behaviour may have changed after increased familiarity with roundabouts and increased saturation levels at roundabouts). It is also necessary to ensure that differences are not affected by data analysis methods. Surveys of smaller single-lane and multi-lane roundabouts that carry moderate demand volumes with no metering signals should be undertaken for this purpose.

Comparisons of measured delay and queue values with those estimated by the SIDRA INTERSECTION software *(1-3,5-8)* for controlling and metered approaches at survey sites confirmed an important issue to be taken into account in the design of roundabouts. Demand volumes at oversaturated approaches will be underestimated as a result of the use of turning movement volumes counted at the give-way (yield) lines rather than demand volumes measured beyond the back of queues. This will result in underestimation of benefits from roundabout metering signals and other intersection improvements, and may result in inadequate design.

Survey data collected during this project indicated that the average queue spacing on approach roads is about 10 m (33 ft) per vehicle (for light vehicles). This is larger than the average queue spacing observed at signalised intersections (for light vehicles, SIDRA INTERSECTION uses a default value of 7 m (23 ft) for the standard left-hand version, and 7.6 m (25 ft) for the US version *(19)*).

The larger jam spacing obtained in this study for roundabouts may be due to the continual flow discharge possible from the front of the moving queue, and this would indicate that the same number of vehicles queued on a roundabout approach would extend further back compared with a signalised intersection.

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