Observational Analysis of Tram Delays in Inner Melbourne

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1 Introduction

The question of priority for street-based public transport has been the subject of recent controversy in the city of Melbourne. Historically the absence of traffic priority measures, combined with the practice of scheduling traffic signals to favour private car traffic, has resulted in very low average travelling speeds for trams and buses. This in turn is a significant factor in passenger deterrence (Mees, 2000).

Official awareness of this issue has risen in recent years, and starting in 2002 there has been an official programme to speed up tram travel. Known as *Think Tram* (Vicroads, 2007), it is jointly led by the State road authority Vicroads, and the private tram operator Yarra Trams. Local councils become involved in the process as plans are developed.

Programmes superficially similar to *Think Tram* in other cities with tram networks have resulted in sizeable reductions in tram travel times. In Zurich, for example, a concerted effort was made starting in the 1970s to isolate and eliminate every source of tram delays. Measures used there have included reprogramming traffic signals to trigger green phases for trams, installing separation barriers between trams and other traffic, and traffic interventions such as turn bans. As a result, Zurich now operates one of the most sophisticated and effective tram priority systems in the world (Transportation Research Board, 2001; Ott, 2002). Judging from this experience, similar successes might be expected from the *Think Tram* programme in Melbourne.

To date, however, outcomes from *Think Tram* have been poorer than in cities like Zurich, when judged against the stated objective of reducing travel times. The perception among passengers is that despite a number of interventions, average tram travel times have continued to increase with the level of road traffic congestion, as is known to be the case with Melbourne buses.[1]

One factor in the limited success of *Think Tram* has been the fact that many of the proposed measures have met with strong community opposition. Most notably, an experiment with departure side stops and kerb extensions in Clarendon Street, South Melbourne, had to be substantially abandoned due to its impact on private car access and movement; meanwhile, proposed changes to tram stops in Collins Street in the CBD have been partially wound back in response to a community campaign.

Tram priority programmes in other cities have generally enjoyed much greater community support and popularity, and it would be easy to dismiss the opposition in Melbourne as nothing more than anti-tram conservatism, stemming from the popularity and status associated with private car travel. It is important to recall however that in Zurich, early proposals to streamline tram services were strongly opposed and ultimately defeated by popular referendum. These included plans to put tram lines underground, to replace some tram routes with buses and to develop a full metro system. Authorities only settled on the current, highly successful tram priority programme after pursuing many such false leads (Mees, 2000, Chapter 5).

Think Tram is, like the early Zurich proposals, open to the criticism that the measures proposed by transport officials (largely without community involvement in their formulation[2]) are

[1] From 2002 onward bus headways on many routes have been reduced from 60 to 70 minutes, with delays due to traffic congestion cited as the reason.

[2] Proposals are typically developed behind closed doors by engineers at Yarra Trams, Vicroads and local councils,

suboptimal from the perspective of the travelling public. This criticism, if sustained, implies that community objections to *Think Tram* projects are quite rational, and that a more participatory approach to the formulation of proposals might yield superior outcomes.

For example, a commonplace observation on the part of passengers is that Melbourne trams appear to spend inordinately long periods of time waiting at red traffic signals. It is therefore likely that a community-focussed process would give much greater weight to traffic signal priority, such as is applied in Zurich to expediting the passage of trams through street intersections. Ott (2002) describes the system (known as SESAM) thus:

> According to the principle that the trams and buses do not need a long green light but do need a green light when they are approaching an intersection, Zurich has developed an almost perfect control concept for traffic lights which is advantageous to public transport. The system can be used at all the intersections regulated by traffic lights (about 300). It works by means of individual signal transmitters in the vehicle and induction loops in the carriageway. . . and can be used by every tram and bus, independently of its time-table. . .
>
> When traffic lights are located directly after stops, the tram or bus signals its arrival at the stop. After 10 to 15 seconds the green light goes on and stays on until the departure signal is given after the vehicle passes. . .
>
> Rather than detecting queues, the system counts vehicles and regulates entry according to local street capacity. Traffic signals at junctions are programmed to give absolute priority to trams and buses, and also to ensure that some capacity is given to pedestrians and cyclists; e.g. if an approaching tram is detected, a short green phase will be given to the crossing flow, both to clear it ahead of the tram and to enable passengers to reach the stop safely.

A consequence of this system design is that 90 per cent of buses and trams are met by a green signal when encountering an intersection (Transportation Research Board, 2001). This is coupled with a computerised location control system which helps ensure that 80 per cent of services run within 30 to 40 seconds of the timetable (Ott, 2002).

Zurich's location control system is not dissimilar to the Automatic Vehicle Monitoring (AVM) technology installed on the Melbourne tram network in 1985 (Yarra Trams, 2007). Nonetheless, *Think Tram* has to date not sought the level of intervention seen in Zurich. It has long been the case that in Melbourne such measures meet with strong resistance owing to the long-standing institutional framework favouring car use over public transport (Engwicht, 1992; Mees, 2000; Laird et al., 2001). As a result, the same institutional structures that provide the technical leadership also tend to oppose measures that are judged to impose added inconvenience on motorists in order to procure an advantage to tram travel.

Alterations to traffic signals have to date been limited to phase insertion: the addition of a special phase to allow trams to pass through intersections between the 'normal' phases, which are still scheduled to favour private car traffic. The more favoured approach meanwhile has been to reconfigure tram stopping patterns, by deleting some stops and moving others to departure-side or mid-block locations. Taken together, these measures have frequently resulted in the perverse outcome where trams stop twice within one city block, having previously made one stop only.[3] This is achieved at the expense of increasing the walking time for passengers who access trams via cross streets where stops have been deleted.

then presented to community representatives as a *fait accompli*. Councillors are urged by their officers to approve the proposals on the basis that the engineers are the 'experts'. While public forums are usually conducted, these are structured as question-and-answer sessions and it is rare for public feedback to influence proposals.

[3]Following the construction of a 'superstop' in Swanston Street adjacent to Flinders Street station, the existing stop on the approach side of Flinders Street (outside St Paul's Cathedral) was deleted. As the traffic signals at this

Evidence-based transport planning—as described for example by Vuchic (1999)—starts from strategic policy objectives (such as the State Government target of 20 per cent public transport mode share by 2020) and an assessment of the existing situation, and identifies the factors with the most promise of achieving the policy objectives. It is reasonable to infer from the government's '20% by 2020' target that there will be some mode shift from private cars to public transport, and that this will be achieved in part through faster travel by public transport even if this comes with some trade-off to travel times by private car in inner-city areas.

In this spirit, this paper documents the initial stage of a research project to quantify the potential benefits of a more Zurich-like approach to tram priority in Melbourne. By making detailed observations of the factors that cause the greatest delay to trams, and comparing the potential time savings with those possible from measures employed to date, it is hoped that a promising new direction for *Think Tram* projects may be identified. Tram priority projects may thereby gain more popular support and demonstrate real success in Melbourne as they have in other cities.

2 'Dead time' as a performance measure

The performance measure chosen for the purpose of this research attempts to strike a balance between the ease and reliability with which it may be observed experimentally, and the ability to attribute causal factors to observed differences in performance. In this case the key factor one seeks to isolate is the lack of traffic priority, the observed effect of which is that vehicles spend unnecessary lenths of time stationary, usually while waiting for a green signal.

The term *dead time* is used, somewhat informally, by traffic engineers to describe 'wasted' time associated with the programming of traffic signals. Often it is used simply to denote the 'all-red' time used between phases to clear traffic from an intersection, but this usage is far from universal, and the term is commonly used more broadly to denote time during a cycle where 'important' traffic is prevented by an adverse signal from entering an intersection. One traffic engineer (County of San Diego, 2006) defined it as follows:

> 'Dead time' in this report is that portion of the green time in the cycle when no cars are moving through the conflict zone. Dead time is an empirical measure that can be performed in the field as adjustments are being made. Measuring dead time is one way of quantifying the effectiveness of signal timing.

In similar vein, the following statement appears in course material for traffic engineers at the University of California, Berkeley (2006):

> Travelers hope that the emergence of "smart traffic signals" will mean less dead time at red lights when there's little traffic on cross streets, and shorter commute times.

Meanwhile, the San Francisco Bay Area Transportation and Land Use Coalition (2002) has applied the term explicitly to traffic priority for public transport:

> Locating bus stops immediately before an intersection has the benefit of allowing the bus to load and unload during the 'dead' time it spends waiting for the light to turn. . .

intersection operate on a cycle time of 2 minutes with just 20 seconds green time for Swanston Street trams, the great majority of trams must still stop at the former location for up to 100 seconds, but no longer board or disembark passengers at this location.

It is accordingly judged that the term *dead time* may be used without confusion to describe our own performance measure for tram priority. Applied to tram operations, dead time is defined as any time during which:

- the tram is stationary, or barely moving;[4] and
- the tram is not boarding or alighting passengers upon arrival at a stop.

This definition of dead time is a compromise between simplicity and efficacy as a traffic system performance measure. It seeks to capture specifically the traffic-system related factors that contribute to delay, while excluding as much as possible factors beyond planners' control (such as delays attributable to passenger action). More specifically, the following factors will contribute to dead time:

- *Adverse signals.* In a system with comprehensive priority for public transport (such as exists in Zurich and some other cities), trams are guaranteed a green signal when ready to depart except in unusual situations. By the above measure, any delay in giving a green signal to a tram that has finished loading and unloading passengers counts toward dead time.[5]
- *Traffic congestion.* Where a tram is stopped or reduced to a slow crawl by queueing traffic, this will contribute to dead time. This factor is to some extent outside planners' control, and mitigation of this factor is more difficult than with adverse signals. Accordingly, a secondary outcome of this research will be a qualitative assessment of the extent to which dead time is attributable to traffic congestion in mixed-traffic conditions.
- *Fouling of reserved track.* Trams are sometimes delayed by private car traffic that impinges on reserved track. Where this occurs, it is usually the result of poor enforcement of rules governing tram lanes. Most tram priority schemes involve police in their management, in order to facilitate the necessary enforcement action.
- *Tram congestion and operational events.* Wherever trams are forced to queue by adverse signals or by breakdowns, transient vehicle faults, short shunting or other such events, trams may incur dead time while approaching a stop that is occupied by another tram.

It is noted that if trams are sufficiently frequent on a section of track, tram congestion is an *expected* occurrence even when there is full traffic priority, and some unavoidable dead time will result. However, for this to be the case in a well-run system, the mean headway must be of comparable magnitude to the mean dwell time at stops. In Melbourne, the mean dwell time required to board and alight passengers is seldom greater than 30 seconds, while the mean headway on the busiest routes is 60 seconds or more. Accordingly, we do not consider that in Melbourne there should be any significant unavoidable dead time due to the sheer number of trams running. In practice, most observed instances of tram queueing are an indirect effect of adverse traffic signals.

Conversely, the following factors will not contribute to the observed dead time, but will contribute to overall travel time:

[4] The 'barely moving' criterion is included to account for the common practice where tram drivers apply the brakes and roll at low speed toward a source of delay, rather than approach the point at speed and then stop. From the perspective of measuring delay the two are identical.

[5] 'Opportunistic boarding', where passengers jump aboard trams that are stopped at red lights but have otherwise finished taking passengers on board, is frequently observed in Melbourne. This can only occur when trams are delayed by adverse signals, and encourages risk-taking by tram passengers, with injuries in car-pedestrian collisions an occasional result. Where public transport receives appropriate priority, passengers lose the benefit of opportunistic boarding but receive a greater benefit in reduced travel time. For this reason we do not deduct time spent in opportunistic boarding from the dead time accumulated at adverse signals.

- *Passenger boarding and disembarking.* Where passengers board and alight in the usual manner following arrival of the tram at a stop, this is not counted in the dead time. Accordingly, dead time does not directly measure the delay that results from high passenger loadings. In principle such delays can be managed by the operator providing additional services, and by preventing cancellations of existing services, but such measures are beyond the scope of this particular study. We also note however that overcrowding can also be a consequence of late running, and it is possible in this way for the problem of delay to compound itself.

- *Variations in cruise speed.* It is a common observation that tram drivers select different 'free' cruise speeds, for a variety of reasons. This is an important factor in the variability of overall travel times, but is not reflected in dead time.

- *Passenger waiting time.* The present study seeks only to measure delays that occur in tram operations, and does not address the problem of variable waiting times for passengers that results from low frequency or poor reliability.

3 Experimental design

Melbourne's tram route 1 commences at East Coburg terminus, on Bell Street approximately 8km north of the city centre, and proceeds along a roughly direct north-south route through the suburbs of Coburg, Brunswick and Carlton to the city. South of the city it proceeds through Southbank, South Melbourne and Albert Park to a beachside terminus on Beaconsfield Parade. Tram route 8 commences at Brunswick tram depot and travels east along Moreland Road, then runs along the same north-south route to the city as route 1. South of the city, route 8 proceeds along St Kilda Road, then travels east along Toorak Road to a terminus at Glenferrie Road, Kooyong.

The present study focusses on the section of this route shared by trams 1 and 8 between Moreland Road, East Coburg, and the city. Together, the two routes provide a high-frequency service that is popular with passengers throughout the day, seven days a week. At the same time, this route is typical of most tram services in Melbourne in that it features a mixture of reserved-track and mixed-traffic running, and runs on streets with a high density of roadside activities. While it has not yet been specifically targeted by the *Think Tram* programme, it has received a number of treatments typical of that programme, including the reconstruction of the stop at Melbourne University and the fitting of tram priority of the phase-insertion variety at a number of intersections along the route. It is envisaged that the results of this research exercise might help inform a future *Think Tram* intervention on this route. As this is also the author's route to and from work it has been relatively easy to obtain a large number of experimental observations in peak-hour conditions.

Of the various traffic-system factors causing delays to trams, the two most commonly cited in anecdotal evidence from tram passengers are adverse traffic signals and traffic congestion. Passenger accounts suggest the former dominates close to the city centre, while the latter dominates in suburban mixed-traffic conditions. To help isolate the effects of these two factors, the study route has been divided into two sections. The northern section, between Moreland Road (Coburg) and Princes Street (Carlton), is 5km in length, suburban in character, and includes a substantial length of mixed-traffic running through East Brunswick. The southern section, between Princes Street and Collins Street (CBD) is 2.7km in length and consists entirely of reserved track.[6] The point of division at Princes Street also coincides with a municipal boundary

[6] On Swanston Street in the CBD the track is 'reserved' in the sense that use is prohibited to most private vehicles, though it otherwise has the appearance of a mixed-traffic route. Part of the hypothesis under test is that delay in this section, as on the unambiguously reserved track to the north, is primarily due to adverse traffic signals.

(between the City of Melbourne to the south and the City of Yarra to the north), hence also with a jurisdictional boundary between two separate traffic management regimes.

For each trip in either of the two route sections, three times were recorded: the trip start and end times (to the nearest minute), and the accumulated dead time as recorded on a stopwatch (to the nearest 15 seconds). In accordance with the definition of dead time, the stopwatch was started whenever the tram completed the boarding and disembarking of passengers at a stop and did not immediately move on (due to an adverse signal or some other factor), and also whenever the tram was stationary or barely moving other than at a stop. The stopwatch was stopped when the tram subsequently moved away.

For southbound travel, the timing points for recording of trip start and end points were:

- Arrival at Moreland Rd / Nicholson St (stop 129);
- Arrival at Princes St / Lygon St (stop 114); and
- Departure from Collins St / Swanston St (stop 11).

For northbound travel the timing points were:

- Arrival at Collins St / Swanston St (stop 11);
- Departure from Princes St / Lygon St (stop 114); and
- Departure from Moreland Rd / Nicholson St (stop 129).

This selection of timing points ensures that delays due to traffic signals at particular intersections are counted in the same route section for both directions of travel.

Another important feature of the study route is the existence of peak-hour clearways north of Brunswick Road, in the section with mixed-traffic running. All the morning peak observations collected during this study coincided with the operating time for the southbound clearway. Conversely, most evening peak observations for the northern section were taken after the clearway finish time of 6pm and will not therefore reflect the existence of the clearway. For the off-peak and late evening observations the clearway is similarly not applicable.

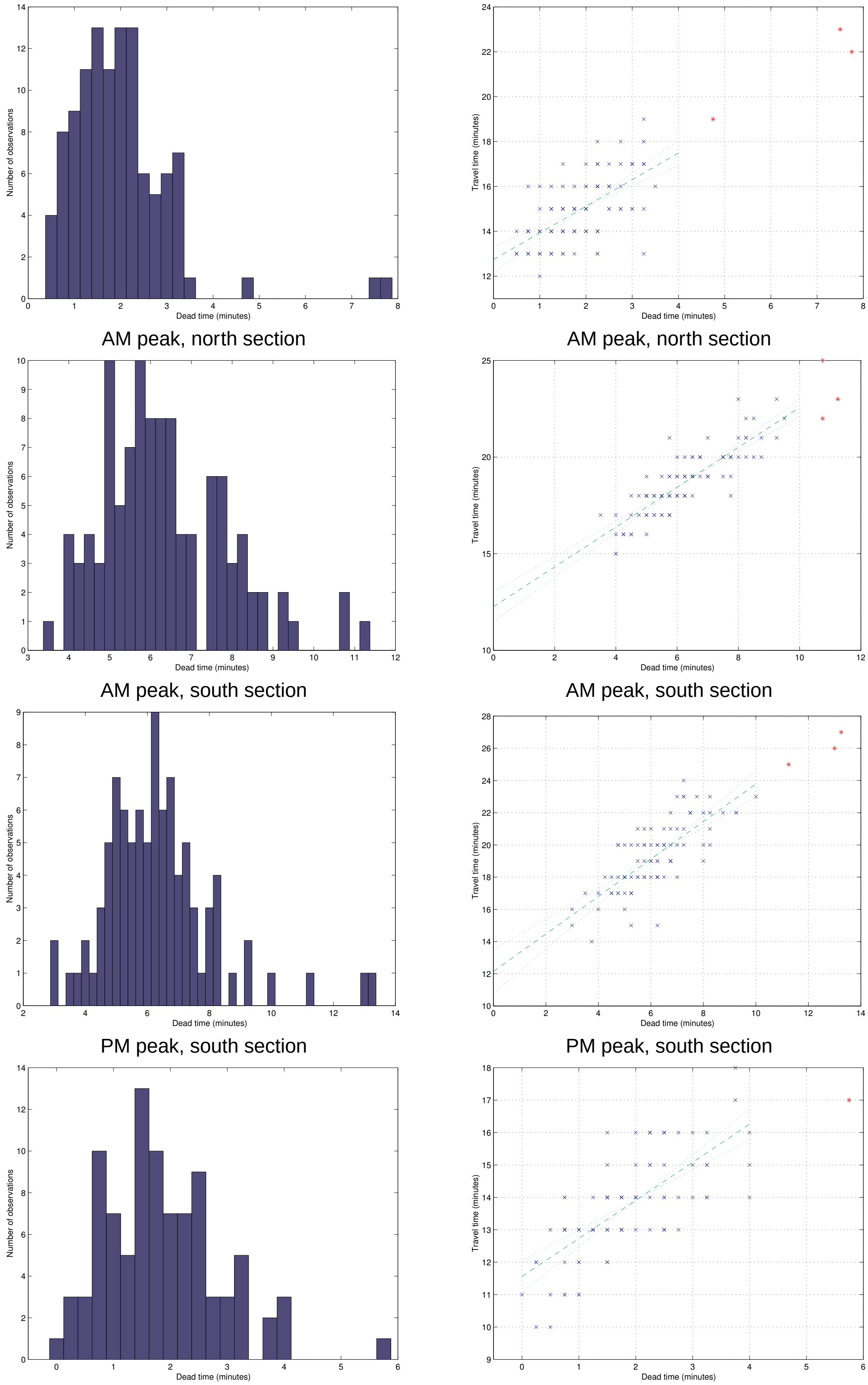
4 Results and discussion

4.1 Key findings

Table 1 presents the summary statistics for peak hour observations of travel time and dead time, over a seven-month period from February to August 2007.

The individual observations are represented diagrammatically in Figure 1. The left hand side shows frequency histograms of the observed dead times for each section; the right hand side presents a scatter plot of travel time versus dead time. Also shown on each scatter plot is the line of best fit obtained from a simple least-squares affine regression of travel time against dead time (see Section 4.2 below). Two further dotted lines indicate the boundaries of the 95% confidence intervals for the y-intercept and the gradient of the regression line. (One line shows minimum intercept and maximum gradient, and vice versa.) The regression analysis excludes the ‘outlier’ observations indicated in red on each scatter plot.

On the whole there is little difference in the travel time characteristics between the morning and evening peak on the same section. Travel is slightly slower on the section of the route where



AM peak, north section | AM peak, north section

AM peak, south section | AM peak, south section

PM peak, south section | PM peak, south section

PM peak, north section | PM peak, north section

Figure 1: Diagrammatic representation of travel time and dead time. (Left) Frequency histograms of dead time. (Right) Scatter plots of travel time versus dead time.

Table 1: Summary statistics for peak hour observations

	AM peak		PM peak	
	North	South	South	North
No. observations	110	108	93	92
Travel time (minutes)				
Mean	15.11	18.80	19.51	13.73
Standard deviation	1.79	1.79	2.42	1.58
Maximum	23.00	25.00	27.00	18.00
Upper quartile	16.00	20.00	21.00	15.00
Median	15.00	19.00	19.00	14.00
Lower quartile	14.00	18.00	18.00	13.00
Minimum	12.00	15.00	14.00	10.00
Dead time (minutes)				
Mean	1.98	6.35	6.34	1.86
Standard deviation	1.12	1.54	1.77	1.02
Maximum	7.75	11.25	13.25	5.75
Upper quartile	2.50	7.50	7.06	2.50
Median	1.75	6.00	6.25	1.75
Lower quartile	1.25	5.25	5.25	1.00
Minimum	0.50	3.50	3.00	0.00
Dead time as fraction of travel time				
Mean	12.7%	33.4%	32.2%	13.1%
Maximum	35.2%	48.9%	50.0%	33.8%
Minimum	3.6%	20.6%	18.8%	0.0%

most passenger boarding occurs (north section in the morning, south section in the evening), and the variability in both travel time and dead time follows a similar pattern, being greatest in the south section in the evening when mean travel time is greatest.

Far more salient is the difference in dead time and in overall speed of travel between the northern and southern section. Recall that the northern section covers nearly twice the distance of the southern section, yet in Table 1 is consistently covered in less time. Based on the mean travel times observed, the average speed in peak hour in the peak direction is around 20kph for the northern section, but in the southern section drops to 8.5kph—a moderate jogging pace.

To some extent, travel is slower in the southern section than in the northern section simply because of the higher density of activities and the higher turnover of passengers in the southern section. But a large part of the reason for travel being as slow as it is in the southern section is the much longer dead time observed. This is clear from the individual observations and also reflected strongly in the statistical evidence. For example:

- The *lower* quartile for dead time on the southern section over the study period was more than twice the *upper* quartile for dead time on the northern section.
- The mean ratio of dead time to overall travel time on the southern section is more than twice that on the northern section. Dead time accounts on average for one-third of the overall travel time in the southern section, but for only one-eighth of the travel time in the northern section.

4.2 Regression analysis of travel time against trip characteristics

To assess the relative importance of dead time in its effect on overall travel time, compared to that of other factors such as late running and time of observation, regression analysis was used to quantify variations in travel time relative to variations in dead time and other trip characteristics. The characteristics used to explain travel time were:

- the recorded dead time;
- the number of minutes by which the service lagged the timetable at the start of the run;
- the actual start time for the run;
- the date of the observation (to capture long term trends); and
- the day of the week (ranging from 1 for Monday to 5 for Friday).

Each characteristic was independently assessed using a two-variable linear model, $T = a + bx$, where T is travel time and x the characteristic in question. The significance of x as a predictor of travel time was assessed using the F-test based on the one-way ANOVA, equivalent to the t-test on the gradient variable; see for example (Devore, 1991).

Based on this assessment the following factors were found to influence travel time.

- Dead time was consistently the most significant of the factors considered, yielding p-values less than 10^{-12} in all cases.
- The start time was found to be significant for the evening peak observations, and for the morning peak on the north section: this is in keeping with travel times according to the timetable, which vary slightly over the course of the peaks.
- The lateness of the tram was on the threshold of significance for the north section (p-values of 0.06 and 0.08 for morning and evening respectively), but not for the south section.
- The day of the week showed a small influence for the south section in the evening peak in the one-variable regression, but this effect did not persist when start time was included as an additional variable. This indicates the effect is most likely an observational artefact resulting from a weak dependence of observation time on the day of the week, rather than a real influence on travel time.
- With the above exceptions no variables other than the dead time were found to be significant in predicting travel time variations, in the sense of yielding p-values less than 0.1 or accounting for more than 5 per cent of the variance in travel time. In particular, no evidence was found for any long-term or seasonal trend in travel times.

Table 2 sums up the results for the regression models found to be significant. First, the results of the two-variable regression against dead time are provided for each of the four groups of observations. Where other characteristics were found significant, the results of a multi-variable regression are also provided.[7] The p-values in each case are less than 10^{-12}.

Note that if variations in travel time were entirely determined by variations in dead time, the gradient in the regression analysis would be exactly 1, and the intercept would represent the

[7] The 'start time' variable used is the number of minutes measured from the median start time for a group of observations, so that the value of the intercept parameter is still meaningful.

Table 2: Results of regression analysis of travel time

	AM peak		PM peak	
	North	South	South	North
No. observations	107	105	90	91
Travel time v. dead time				
Intercept (min)	12.74	12.26	12.15	11.56
Gradient (min / min)	1.19	1.03	1.16	1.17
Coeff of determination R^2 (%)	39.59	73.03	56.74	50.90
Travel time v. dead time and other characteristics				
Intercept (min)	12.88		13.52	11.73
Gradient: dead time (min / min)	1.08		0.98	1.14
Gradient: start time (min / min)	0.04		-0.03	-0.01
Gradient: minutes late (min / min)	-0.13			-0.02
Coeff of determination R^2 (%)	43.88		69.19	55.79

'free' travel time where the only delays are those inherent to the transport task. The closest fit to this situation occurs for the southern section of the route (in the PM peak case, after adjusting for a start time effect equivalent to about 2 minutes reduction in travel time per hour). For the southern section, dead time is found to account for around two-thirds of the variation in travel time, and the prospective improvement in average travel speed from eliminating dead time is around 50 per cent.

For the northern section, dead time accounts for one-third to one-half of the variation in travel time, but with a gradient in excess of unity. This, together with the reduction in gradient that occurs when other regression variables are added, indicates that increased dead time is weakly correlated with other factors that cause delay to trams. One possible explanation for this effect is that delays to one tram, however caused, can result in congestion delay to a following tram, which will manifest as increased dead time.

Lastly it should be noted that the recording of start and end times to the nearest minute introduces a systematic error into the travel time variable: the error has zero mean but a theoretical variance of 0.17 minutes-squared. This error variance is found to be less than 10 per cent of the observed variance in travel time for each group of observations, and is not judged to be significant for the analysis.

4.3 Observed factors contributing to dead time

In qualitative terms, when ranked by relative contribution the factors contributing to dead time were: adverse traffic signals, traffic congestion, fouling of reserved track, tram congestion, and operational events. Adverse traffic signals accounted for a clear majority of the dead time in almost all observations, other than the small number affected by operational events such as breakdowns. Traffic congestion generally had a significant impact only on evening peak travel in the northern section (except as noted in Section 4.6 below), and the dead time contributed was typically in the order of one minute. Tram congestion was a relatively minor factor in dead time, even on the highly utilised southern section, and where it occurred was often a flow-on effect of adverse traffic signals (where multiple trams queue up at the same red light).

It has already been noted that the observed dead time is much less on the northern section than on the southern section. In fact it was common for over 50 per cent of the dead time on the northern section to be recorded at adverse signals at just one or two intersections: typically

Moreland Road, Albion Street or Brunswick Road where signals provide substantial green time to cross traffic. A typical example is the 28 May PM observation, where of the 75 seconds of total dead time recorded, 45 seconds were incurred at Brunswick Road; or the 6 June AM observation, where of the 135 seconds total dead time, 60 seconds was incurred at Albion Street and a further 30 seconds at Brunswick Road.

4.4 Delays not reflected in dead time

The most common source of delay *not* reflected in the dead time was delay in boarding and alighting passengers resulting from overcrowding. Excessive ovecrowding resulting in delay is not consistently observed; it affects only a minority of runs, and can usually be attributed either to cancellation of the preceding service, or to irregular timing of services.

Irregular timing is most apparent in the morning peak. On the northern section, routes 1 and 8 are timetabled to alternate at regular intervals of approximately 4 minutes. Nonetheless, it was commonly observed that at Moreland Road where the two routes converge, two services would depart less than a minute apart. As it was rare for the route 1 tram to run late by more than 1 or 2 minutes at this point, the apparent cause is late running of the route 8 service along Moreland Road.

A plausible explanation for this observed behaviour is that after departing Brunswick Depot, the route 8 tram must negotiate two sets of traffic signals: one to enter Moreland Road from a side street, and one to cross Sydney Road at Moreland Road. Both these sets of signals have long cycle times (typically 120 seconds), are set to favour traffic movements conflicting with the route 8 tram, and do not provide any priority to waiting trams. These factors operating together result in unpredictable dead time of up to 4 minutes for the route 8 tram. The same factors result in the formation of long queues of cars at the Sydney Road intersection, causing further tram delays.

4.5 Notable observations and outliers

On a few occasions over the seven-month study period, the observations were confounded by extensive delays due to tram breakdowns. For the most part, such events were treated as ‘one-off’ incidents and no observations were recorded. However, there were occasions (such as in the morning peak on 29 March and 2 April) where similar events occurred more than once in a single seven-day period. Such events cannot be entirely written off as chance occurrences. Accordingly, for the second and subsequent occurrences of these events less than a week apart, a time observation was recorded based on what an ‘informed commuter’ would experience: typically a walk to the nearest shunting point followed by a wait for the next tram. The walking and waiting time are added to the recorded dead time. While such observations count toward the averages, they are treated as outliers in the regression analyses (and shown in red on the scatter plots in Figure 1).

The issue of tram breakdowns is not wholly irrelevant to questions of signal priority. Breakdowns typically result in the formation of long queues of trams, which in the absence of priority must then filter through unfavourable traffic signals one or two at a time after the tracks are cleared. For this reason, what would be a minor inconvenience can escalate into a major system failure. For example, in the presence of signals with a 2-minute cycle time and green time permitting the passage of at most two trams, a queue of 20 trams requires 20 minutes to clear even after the breakdown is resolved. On Swanston Street, trams are scheduled at the rate of approximately one per minute, so the above scenario would result whenever a breakdown occurs requiring 20 minutes to be resolved. It would then be the case that the breakdown itself is responsible for only 50 per cent of the resulting delay, with the other 50 per cent due to the effect of traffic signals.

Operational events other than outright breakdowns appear as outliers in the results. One such significant outlier is the northern section time on the morning of 24 May. This includes a delay of over six minutes due to an operational event, namely non-attendance of a relief driver at Moreland Road. Excluding this event the travel time for the section was 15 minutes and the dead time 60 seconds, consistent with the average timings on this section. Another is the northern section time on the evening of 31 May, which was affected by an overhead power outage lasting 4.5 minutes. Excluding this event the travel time was 13 minutes and the dead time 75 seconds, slightly below the average for this section.

The observation for the northern section on the morning of 4 June, while not statistically atypical, is technically an outlier as it includes two minutes of delay and dead time due to the atypical event of a preceding tram becoming 'defective' and transferring all its passengers to the tram under observation. The travel time performance exclusive of this event was better than average, with 14 minutes travel time and 30 seconds dead time.

4.6 Effect of morning peak clearway

It has also been possible to obtain some evidence of the effect of the Lygon Street clearway on morning peak travel times.

Three morning peak observations—on 26 April, 30 April and 10 May—included the effect of traffic delay due to blockage of the kerbside lane by a parked car in East Brunswick, just north of Glenlyon Road. While the additional congestion on these occasions was tangible, the additional dead times attributable to the blockages as recorded on the stopwatch were 60, 45 and 45 seconds respectively: roughly the same as for one mistimed set of traffic signals. Significantly, the congestion incidents on 26 April and 10 May accounted for only one-third or less of the total dead time on this leg of the trip, and while the overall travel times (17 minutes) were significantly above average, there are many instances within the time series of similarly adverse travel times where blockage of the clearway is not a factor. Conversely, on 30 April the recorded travel time (13 minutes) and dead time were both below the average for this leg (as well as below the average for Mondays alone).

On 30 May, a morning peak observation was similarly affected by blockage of the clearway in Holmes Street north of Albion Street in East Brunswick. This also resulted in a delay to the tram, with maximum attributable dead time of 45 seconds. Nonetheless, the total dead time recorded on the section was, at 105 seconds, slightly below the mean. Elapsed travel time was equal to the mean for this section, at 15 minutes.

It may be concluded on this basis that peak-hour clearways in mixed-traffic situations are beneficial. However, the overall benefit over this section of route is almost certainly less than what one would obtain from full signal priority.

4.7 Observations outside peak times

During the study period a small number of observations were collected outside the weekday morning and evening peak periods. These were classified into daytime journeys (both to and from the city) and late-evening journeys (from the city only), and are summarised in Table 3.

To some extent these additional observations serve as a control for the effect of overcrowding and 'high passenger activity' on travel time, as these journeys were not greatly affected by overcrowding. In this regard it is of interest that the statistics do not differ markedly from those for peak journeys in Table 1. Specifically, the dead times observed during the day are typically around 80 per cent of those observed in peak hour, and only in the late evening is the dead time substantially reduced for a typical journey.

Table 3: Summary statistics for observations outside peak hour

	Day: to city		Day: from city		Night: from city	
	North	South	South	North	South	North
No. observations	11	6	3	6	15	16
Travel time (minutes)						
Mean	12.64	16.17	15.33	12.67	14.40	11.00
Standard deviation	1.57	1.72	1.15	2.58	1.55	0.89
Maximum	15.00	18.00	16.00	17.00	17.00	12.00
Median	13.00	16.00	16.00	12.00	14.00	11.00
Minimum	10.00	14.00	14.00	10.00	12.00	10.00
Dead time (minutes)						
Mean	1.36	5.96	4.83	1.67	3.80	0.55
Standard deviation	0.56	1.78	0.95	0.98	0.79	0.44
Maximum	2.25	8.25	5.50	3.25	5.00	1.50
Median	1.50	5.88	5.25	1.50	4.00	0.50
Minimum	0.50	3.75	3.75	0.50	1.75	0.00
Dead time as fraction of travel time						
Mean	10.7%	36.2%	31.3%	12.5%	26.2%	4.96%
Maximum	16.1%	45.9%	34.4%	19.1%	30.8%	12.50%
Minimum	4.6%	26.8%	26.8%	5.0%	14.6%	0.00%

It is apparent from the figures that the difference in mean travel time between peak and off-peak periods is primarily due to reduced passenger activity and not to systematic differences in dead time. However, the fact that dead time is still very high, particularly for the southern section, indicates that measures aimed at reducing dead time would yield improvements to travel time similar to those attainable in peak hour. Owing to the relatively small number of off-peak observations there is little that can be gleaned from a regression analysis; however an indicative analysis strongly supports the hypothesis that dead time accounts for the majority of the variation in travel time from one off-peak journey to the other, just as it does for variation in peak travel times.

5 Conclusions

Observations have been conducted of travel time and delay on one Melbourne tram route over a seven-month period. The study provides significant evidence for the following conclusions in regard to the study route:

1. ‘Dead time’ is a significant predictor of the variation in peak hour travel time, accounting for two-thirds of the variation in the southern section of the study route (within the City of Melbourne boundaries) and one-third to half of the variation in the northern section.

2. The most significant factor contributing to dead time is adverse traffic signals, with other significant factors being traffic congestion, fouling of tracks, tram congestion and operational events. With the exception of traffic congestion, the occurrence of these factors is largely within the control of transport authorities.

3. Within the City of Melbourne boundary, dead time accounts on average for one-third of overall travel time, with a mean of nearly 6.5 minutes out of 19 minutes. This dead time

accrues despite the tram running on reserved track where it is not subject to significant traffic congestion.

4. Outside the City of Melbourne, dead time accounts on average for about 13% of overall travel time, with a mean of nearly 2 minutes out of 14–15 minutes. Traffic congestion does not always contribute to the dead time, but when present its typical contribution is in the order of one minute.
5. The elimination of dead time, were it possible, would improve average travel speeds for trams in peak hour by around 50% within the City of Melbourne and by around 20% further north.
6. Lack of punctuality (itself largely a consequence of adverse traffic signals) is an indirect contributor to delays, as a consequence of overcrowding.
7. The presence of a clearway can avoid additional dead time due to traffic congestion of up to 60 seconds on a 2km stretch of mixed running, though this effect is not consistently observed. The effect is smaller than the additional dead time contributed on average by adverse traffic signals on the same section of route.
8. The mean dead time observed off-peak is around 80% of that observed at peak times, except in the late evening. Overall there is little qualitative difference in the dead time characteristics between peak and off-peak times, although travel times are reduced likely as a result of reduced passenger activity.

Our primary recommendation stemming from these conclusions is that tram priority measures must concentrate primarily on expediting the movement of trams through signalised intersections, in similar vein to the scheme employed in Zurich, and not simply through the phase-insertion approach already in place. Particular effort needs to be directed toward signal priority within the City of Melbourne boundary.

A secondary focus should be on the other factors that contribute significantly to dead time and are within planners' control: these include enforcement of tram lanes, maintenance practices to minimise breakdowns in service, improved operational management, and better adherence to timetables (facilitated by better signal priority, together with better use of AVM and similar systems to improve reliability).

Compared to these changes, the effect of currently popular measures such as extension of clearways and deletion of tram stops is likely to be marginal at best, not to mention highly unpopular with the general public.

The promised implementation of 'Dynamic Signal Priority' by Vicroads, if followed through, is a potentially significant step in the recommended direction. If designed properly this has the potential to bring Zurich-style priority to tram and bus routes in Melbourne. However, at present it is unclear that it will be employed to its full potential, and not simply used in the same fashion as the more limited priority schemes to date, as a means to assist late-running vehicles catch up to the timetable. The findings of this paper would support a more wide-ranging implementation of dynamic priority.

It is also perhaps counter-intuitive that a significant factor in delays on the studied route is the performance of the Moreland Road–Sydney Road intersection, which is outside the study area. The reason, as explained above, is that by reducing the predictability of running time on the northernmost portion of tram route 8, it results in the downstream effect of irregular headways in the northern section of our study area and excessive overcrowding when particularly large gaps occur.

Poor performance of the Moreland Road–Sydney Road intersection is to some extent an inevitable consequence of high car traffic volumes, for which there is no 'quick fix'. A key factor is the long cycle time, which is currently considered necessary in order to maximise the capacity for north-south car traffic in Sydney Road.[8] However, the implementation of dynamic priority at the exit from the tram depot to Moreland Road, coordinated with the Sydney Road signals, would help mitigate the problem by effectively shifting the queueing point for eastbound traffic in Moreland Road by some 200 metres, from the Sydney Road intersection to the west side of the Upfield line. This would not markedly affect the degree of congestion, but would provide a relatively uncongested path for the route 8 tram between the depot and Sydney Road.

The study reported in this paper is one small contribution toward a body of published evidence that could assist in planning and policy decisions but which is currently lacking. Similar studies on other Melbourne tram and bus routes would assist public transport planners and operators gain a better understanding of the factors affecting the performance of their operations and their effectiveness as a convenient alternative to car travel for the general public.

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[8]As Sydney Road itself carries a tram route and runs 200 metres away from the Upfield train line, the wisdom of prioritising travel by car in competition with two parallel public transport routes might be questioned; at the very least, it points to a worrying disconnect between road planning and public transport planning in Melbourne.