Costing Traffic Congestion

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Abstract

Ever since people began moving around with power and purpose, traffic congestion has had a significant impact on regional economies, land use, the environment and the quality of our lives. While many researchers have offered various definitions of traffic congestion, there is no universally accepted definition. Furthermore, different variables have been introduced to measure traffic congestion. Because traffic congestion is so ill defined, many misconceptions and invalid arguments have been used to provide past and current estimates of the extent and cost of traffic congestion. This paper aims to examine the existing methodologies used to assess congestion and to introduce improved approaches to how it is measured and costed. The discussion is illustrated in part by an incomplete study of a highly congested corridor in Melbourne, Australia. The findings and conclusions of the paper include a better understanding of the process of urban congestion leading to better processes for estimating its extent and cost, to improved methods of congestion management and to changed modelling approaches for conditions of heavy and/or uncertain demand.

Introduction

Traffic congestion is a daily part of most metropolitan cities throughout the world. It has a considerable impact on metropolitan economies, land use, local environments and the travel behaviour of millions of road users. The impact of traffic congestion is therefore an important consideration for city managers, urban planners and transport operators.

The cost of traffic congestion is thus a widely used parameter in transport planning and urban decision-making. It frequently features in media ranging from political statements, planning proposals, governmental reports, consultants' reviews, project analyses, papers in learned journals, and doctoral dissertations. As an example, a well-publicised 2014 study by INRIX – a US group with strong links to the automotive, transport and computing industries – included the following claims.[1] With astonishing confidence it predicted with three-figure accuracy that the annual cost of congestion in Los Angeles in 2030 would be "$38.4B". It also calculated that people in Europe and the USA were currently "wasting on average 111 hours annually in gridlock". This might also seem a big number but a typical traveller would make at least about 500 trips a year so "wasting" about 10 minutes per trip on *gridlock* - whatever it might be - does not seem all that significant. Nevertheless, most congestion analyses indicate that the value of time is a major determinant of congestion cost and this aspect will be discussed further in this paper.

For urban traffic links, the application of speed limits reduces travel speeds as vehicles move from motorways to urban roads. Some of the simpler methods used for calculating the cost of congestion compare measured trip travel times with an idealised, often free-flow[i], trip time. In 2015 the author was involved in a case where an on-line traffic service had reported a dramatic increase in congestion in a major North American city. The locals were bemused by the reports as their congestion seemed to them to be a lot less severe than in other comparable

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[i] Free-flow occurs when a vehicle's travel behaviour is not influenced by other vehicles.

cities. It transpired that report reflected not congestion but a consequence of the delays caused by the lower speed limits the city had introduced on some of its urban streets in order to protect and aid pedestrians and cyclists.

Prior to 2015 most Australian estimates of congestion costs were produced by the Bureau of Transport and Resources Economics[2] (BTRE) and were based on a very broad and coarse modelling of a city's traffic and on unrealistic congestion assumptions.[3] In a 2015 report,[4] a newer national government agency, Infrastructure Australia (IA), adopted a more focussed approach and estimated that the annual cost of congestion in Australia was $13.7 billion in 2011 and would rise to $53.0 billion in 2031.[5] For Melbourne the figures were $2.8 billion rising to $9.0 billion. The IA estimate was supported by a group of Veitch Lister reports[6] based largely on traffic forecasting studies and which noted, inter alia, that the Eastern Freeway - Alexander Parade corridor in Melbourne was operating at close to capacity in 2011. Section 7.4 of the IA report stated *"volume/capacity (V/C) ratios are used to gauge the level of congestion in the road network"*. The process of doing this was not explained, which is unfortunate as there is no simple and direct link between V/C values and the common congestion processes to be described in this paper and which occur over significant periods in which the incoming traffic volume equals or significantly exceeds capacity (V/C>1).

Common traffic congestion measures were critically reviewed in 2011[7] and then by Yumlu et al[8]. In general, most of the advocated measures were found to be inadequate for their various proposed usages. Thus in this respect the INRIX and IA reports discussed above are far from unique.

Defining congestion

The first step in a rational costing of congestion is to define "*congestion*", particularly as the current definitions in use are commonly either very vague or poorly structured. The author has previously explored this issue in some detail.[9]

In the 19th century the word "*congestion*" had been used in medicine to describe the deleterious accumulation of phlegm within the human lungs and it was quite appropriate to transfer the term across to describe early 20th century cases where traffic exceeded processing capabilities of the traffic system.[10] In traffic theory and traffic engineering practice, this system processing capability is usually the key capacity parameter used in modelling traffic operations[11] and will be discussed further below.

This paper defines "congestion cost" as a "system operating cost" which only includes the extra vehicle operating costs and time costs incurred by travellers and cargo due to congestion. It does not include environmental (pollution-caused) costs, crash costs or other "*social costs*". These social costs are sometimes used by economists to add a further "*social dimension*" to the calculation of congestion costs, as in the following two examples:

> *Congestion may be regarded as the point at which an additional road user joins the traffic flow and affects marginal cost in such a way that the marginal social cost of road use exceeds the marginal private cost of road use at the "optimal" level of congestion.*[12]
> *Congestion costs are incurred when the traffic flow exceeds an optimal level and each user has to pay not only increased private costs of the trip but also the external costs for the time losses caused to other users, given variations in demand according to time and place.*[13]

Both these definitions unrealistically presuppose that drivers in making their travel decisions have an accurate awareness of *marginal costs* and of *optimal levels of congestion*. The methods in this paper could be readily be extended to aid in retrospectively calculating these variants of congestion cost but they are not the thrust of this paper.

Congestion costs calculated by the methods proposed in this paper are based solely on the operation of the traffic system. Specifically, these are (1) the costs of the extra travel time incurred by travellers and cargo and (2) the extra vehicle operating costs due to stopping, starting, idling and travelling at sub-optimal speeds. A key finding will be that in most cases the major component of congestion cost is the cost of time delays. It is useful to explore this finding in more detail. In many ways it would be simpler to measure congestion in terms of accumulated extra time, particularly as this would avoid the need to convert time into cost. However this would prevent a proper accounting for the cost of delaying buses and trams laden with passengers and trucks carrying valuable cargo.

The cost of time of the extra travel times due to congestion has always been debatable and time is best left as an algebraic variable for as long as possible. For the purposes of this paper it will be assumed that such travel times can be converted into congestion costs by multiplying by a dollar value. Typically, planners use 70% of the average direct salary in the region.[14] A convenient working assumption for Australian conditions is that the value of time is $1/minute (although a more realistic value might be closer to 80c/minute). A major dilemma with more intricate costing of extra travel times due to congestion is that many commuters accommodate the extra time by leaving home earlier and/or arriving home later. They sacrifice part of their 24 h day to travelling in congested conditions rather than make more direct economic trade-offs. Costing based on average salary is a poor surrogate for such losses and trade-offs.

The traffic system

A traffic network can be considered as an operating system. Traffic which enters the system is processed by the system. When the rate of traffic entering the system exceeds its processing capability, the excess traffic is stored at either the entry points or at various points within the system. A contemporary example of entry point storage is provided by traffic at or upstream of a motorway entry ramp with operating ramp-metering signals. When processing capabilities are exceeded, the stored traffic may reach levels that will degrade the perceived operation of the system.

An urban traffic system can be considered to consist of three parts: (1) system entry and exit points, (2) internal links, and (3) intersections between links.

It is useful to begin by discussing the occurrence of congestion at intersections. At these locations traffic on one link may come into conflict with traffic on another link. The conflict is managed by traffic rules (e.g. give way to the right, give way to circulating traffic at a roundabout), traffic signs (e.g. Stop) or traffic signals. The first two occur in any traffic system. Stop signs stop all vehicles, even in light traffic. Similarly, some delays may be due to safety considerations separating individual vehicles, as at roundabouts. As a further example, in most practical traffic networks travel speeds on links may often will be limited to below free-flow speeds by urban speed limits. Traffic signals are an inevitable and inherent part of a busy urban traffic system and their operation is major determinant of the capabilities of that traffic system. The delays that these various processes cause are often not a consequence of excess traffic (i.e. congestion) and it is wrong – as some studies have assumed – for all intersection delays to be considered part of congestion costing. A number of common congestion costing methods incorrectly assume that any travel time at less than free-flow travel times will contribute to congestion costs.[15]

As traffic in an urban area increases, the first symptom of intersection congestion would be when the number of vehicles approaching it first exceeds its capacity. The most relevant case is the signalised intersection and in this case capacity is the number of vehicles that can pass through the intersection during one cycle of the signals. In system stability terms this *overflow* case can be thought of as a congestion horizon signalling a change in the state of the system. If at least one vehicle is left over at the end of a cycle then this residual vehicle will add to the demand in the next cycle, even if the arrival rate stays constant. For a simple illustrative case of a 180 s signal cycle evenly split, a vehicle would have an average delay of about 25 s whereas overflow (or residual) vehicles would have a delay of at least a full 180 s – an order of magnitude increase. Of course, the congestion delay would not include average delays in the pre-overflow case.

Using the above illustrative \$1/minute cost of time and 3-minute signal cycle puts the congestion cost to a vehicle passing through an intersection at the first congestion horizon at about \$3. In an urban area there could be 3 intersections per kilometre which puts this horizon cost at about \$10/km. However, total car operating costs are about \$0.5/km.[16] This broad-brush analysis indicates that the value of passenger and cargo time at \$10 is an order of magnitude greater than vehicle operating costs at \$0.5 – even at this early congestion stage – and thus illustrates why time delay is the dominant factor in congestion costing.

This view can be explored further with much more precision by using the SIDRA INTERSECTION[17] software which has quite detailed models for assessing these costs for a range of different configurations. The software will be referred to as SIDRA in the rest of this paper.

SIDRA can track individual traffic flows through an intersection on a lane-by-lane and movement-by-movement basis (a traffic movement is a path that a vehicle can follow through an intersection). It does this using appropriate traffic modelling principles, including overflow queue modelling, and has the ability to calculate the travel times, fuel consumption, emissions and vehicle operating costs for a wide range of circumstances.

Note that any SIDRA-based analyses and field data partially reported in the latter part of this paper were part of a discontinued graduate research program at RMIT University. The completed work demonstrated the appropriateness of SIDRA for congested traffic[18] and that, for the intersections studied, time delays caused over 90% of congestion costs.

Recall that the worsening situations described above do not require the traffic flow to increase beyond just one vehicle above the capacity of one intersection. The next stage of the intersection component of the congestion process can commonly be of two forms. The first form occurs when the queue of vehicles left over at the end of green phase prevents the previous upstream intersection from discharging all its traffic or even blocks the upstream intersection. The second form occurs when the available queue capacity at the downstream intersection is less than that needed to accommodate the traffic leaving the intersection being studied, possibly as a consequence of turning movements, pedestrian flows or residual overflow vehicles downstream of that intersection. As a specific example, traffic regulations commonly prohibit a driver from entering an intersection if the driver is not confident that driver's vehicle can clear the intersection during the green phase. On the other hand, if this prohibition is ignored cross- and turning-traffic can also be blocked.

Such situations where excess demand at one intersection leads to blockage at other intersections create new congestion event horizons. Even if the traffic inflow is steady, the cost of congestion will increase at a greater rate than prior to the blockage due to the consequential capacity reduction of other traffic lanes.

Finally, such blockages can be the trigger point for a situation where no flow is possible and this congestion horizon is generally described as *grid-lock*, based on pioneering congestion observations by Vickrey in New York in 1967.[19]

As defined above, the second part of the traffic system is comprised of the links between intersections. In the absence of a speed limit, the traffic flow on a link will depend on the driver's assessment of a safe-time separation between vehicles.[20] If unexpected interruptions are unlikely, drivers might adopt a headway time of 1.5 s leading to a lane capacity flow of 2,400 veh/h on freeways. The commonly used lane capacity value of 1,800 veh/h assumes a headway time of 2 s on arterial roads. This is close to the maximum sustainable flow measured in recent studies by VicRoads.[21] This flow has no congestion component and recent move to "managed motorways" discussed below is primarily directed towards preserving this congestion-free operation. It will commonly require speeds in excess of speed limits on roads in urban networks.

The third part of the traffic system is comprised of the points of entry and exit to the system. Drivers arriving uninhibited at an entry point at a higher rate than the receiving links can accommodate will form moving queues and force their way into the line of link traffic. This will reduce vehicle speeds and spacing, thus resulting in increased headway times and reduced flow rates. The managed motorway methods mentioned above are designed to address this issue by maintaining maximum sustainable flows on the receiving links. This is done by using coordinated signals on entry ramps to limit the size of the entry flows to a level that avoids the unstable flows that would otherwise occur if drivers on the link had react to an excess of intruding vehicles.[22] The consequential congestion cost is calculated by measuring the time vehicles spend on the entry ramp – and perhaps at blocked upstream intersections – and subtracting the hypothetical time a vehicle would spend passing through the entry point in absence of ramp metering.

The entry points of major concern in costing traffic congestion in a traffic system are often in AM (inbound) peaks when motorways deliver traffic to a conventional urban road network. A major factor is that peak urban lane flows – due to speed limits and traffic signals – will commonly be less than 1,000 veh/h. If the motorway link is delivering about 2,000 veh/h, this difference will lead to a rapid growth of queues at exits. This difference may be further exacerbated by the fact that often more than one motorway lane will be served by a single urban traffic lane. The cost of exit point congestion can usually be simply calculated by measuring the excess time vehicles spend in slow-moving queues waiting to be serviced by an exit point.

The capacity constraints at signalised entry-point intersections can have some beneficial effects as the flow of discharging traffic will commonly be compatible with the flow capacity of downstream intersections. Thus the newly created platoon of vehicles leaving the first intersection could be expected, in the absence of new cross-flows and joining flows, to experience lower congestion costs at downstream intersections.

It is important to note that the approach reported in this paper suggests calculating the cost of traffic system operation under a given set of traffic flows and subtracting from that value the cost of the same system when operating at traffic flows at the onset of the congestion horizon stage at which the increased traffic flows begin to cause a new set of delays to occur. This is consistent with the view that stopping at traffic signals for up to one cycle of the signals is a normal traffic situation resulting from a conventional urban road network and does not in itself indicate that the network is congested.

Testing the paper's congestion propositions

A core proposition of the paper is that most traffic congestion is not some random, unpredictable event, but that its components can be predicted, observed and modelled, and as such, used to predict congestion consequences, particularly costs. To test this proposition and to provide some specific outcomes, observations were made of one part of a real traffic system.

The site chosen was in the eastern part of Melbourne, Victoria, Australia. It is a linear AM traffic route travelling west on the M3 Eastern Freeway from west of its interchange with Chandler Hwy to its western end at Hoddle St and then west along Alexandra Pde up to and beyond its intersection with Smith Street, a travel distance of about 3 km of motorway and 1 km of arterial road (Fig. 1). The intersections are part of a Melbourne metropolitan co-ordinated traffic signal network controlled by the SCATS program.[23]

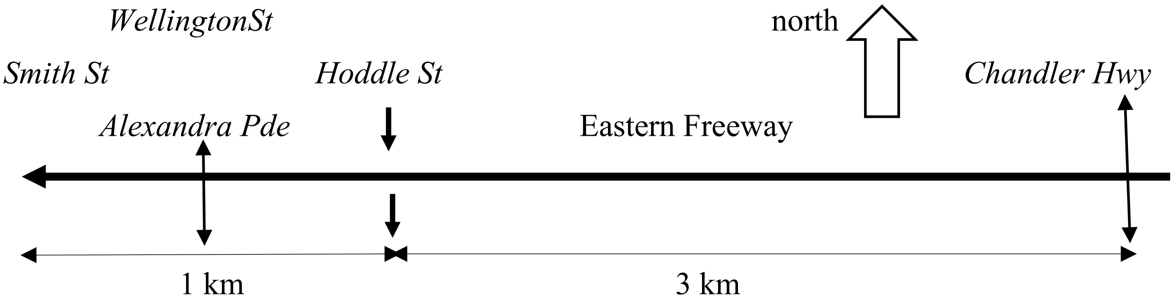

Fig. 1 Diagrammatic map of study area

The route was a divided highway for its entire length and contained two signalised intersections at Wellington St and Smith St. These two streets have a single carriageway across Alexandra Pde. A button-operated school crossing 120 m east of Wellington St had no significant impact – mainly because the queues extended well east of the crossing during school hours. There was no public transport on the route (a separate bus lane on the southern side of the Freeway does not play a role in the traffic flows studied as it turns south onto Hoddle St at the western end of the Freeway and had no influence on Wellington St). Smith St has centre-of-the-road trams (street cars). There is minor bicycle traffic along the route, although Wellington St does carry relatively heavy south-bound cycle traffic.

Due to two historical accidents,[24] both segments of the study route have a very wide (30 m) signalised median. The eastern (upstream) part of the freeway segment has five lanes with those on the left (southside) servicing traffic leaving the freeway to head south or north on Hoddle St. The lanes on the right (northside) service three lanes of Alexandra Pde traffic preceding west in the study zone. On the day of the completed traffic survey, 54% of the traffic headed west. The larger vehicle spacings shown in Fig. 2 for part of the west-bound traffic reflects vehicles adjusting to the new lane configuration and a high-occupancy vehicle provision in the furthest north lane. These vehicles had all come from longer almost-stationary upstream queues. Turning movements on Alexandra Pde were relatively small and were often catered for by separate turn slots. The system described provided an effective study route with two links, one entry (the freeway just west of Chandler Hwy and one exit point (Alexandra Pde east of Smith St) and two intersections.

Fig. 2 Looking east and showing the Eastern Freeway westbound approach at 8 am on 19 Sep 2012. The split in the foreground is between west-bound (on the left) and north-south bound (on the right). J B Metcalf photograph.

Modelling the traffic

As commonly used, the SIDRA Capacity Model is calibrated using intersection stop-line and saturation flows per lane and signal timing data. In Melbourne these can be obtained directly from SCATS. In relevant cases lane blockage surveys are also required. However, it soon became obvious[25] that at entry points with long upstream (arrival) queues the model must be used in two stages, namely an analysis based on stop-line *capacity* flows under congested (*oversaturated*) conditions obtained from the SCATS data, and an analysis based on *demand* flow rates obtained from upstream freeway flow data and the long queues that were observed.

The capacity analysis was conventional although field tests showed[26] that lane blockage at the Wellington St intersection reduced the saturation flows per lane from (approximately) 1,800 veh/h to 850 veh/h. The demand model depended on specific local conditions which relate to the long queues extending upstream from the Wellington St entry point. *Demand flows* were obtained as arrival flows at the upstream back of this queue. The importance of using demand flow data under congested conditions and considering the impact of queue spillback on reduced saturation flow rates and capacities was an early outcome of the study[27]. The lane-based network model employed in SIDRA INTERSECTION was able manage these two factors.[28]

SIDRA INTERSECTION's lane-based analytical modelling using overflow theory was found to be more appropriate for identifying the role of overflows in congested cases than other software packages used for intersection analysis. Microsimulation packages which mimic the individual vehicle movements using such model elements as car-following, lane changing and gap acceptance did not provide a direct analysis of overflow conditions at intersections.

Field data related to entry point queues

The specific entry point under consideration comprised the inbound lanes of the Eastern Freeway leading to Wellington St. While some data used in this study were provided by the local road agency, VicRoads, the initial study added on-site data collection to consider the development of queues and the subsequent effects of the queues.

It was soon observed that once the trigger event for a persistent overflow queue occurred, i.e. queued vehicles remaining at the end of a green phase, the queue length increased quickly and, at its peak, was about 3 km long. Drivers might be waiting for up to 10 cycles of the Wellington St signals before they finally passed through the set of intersections analysed. Although stop-start conditions persisted at the front (western end) of the queue, at the tail (eastern) end of the queue, drivers could see the long queue ahead and modified their driving so that many rarely came to a full stop and the detailed impact of the signal changes was soon lost. This fact was exacerbated by the fact that – due to local curvatures of the approach lanes – the signal displays could not be seen until drivers were within about 200 m of the display. That is, they might only have seen the last one of some 5 to 10 red signal phases and so their driving in the queue appeared to be based on their observation of the speed of queuing traffic in the queue ahead of them. As a result there was often not a precise tail of the queue.

A related set of observations was obtained from a "floating" car travelling in the traffic and behaving in the same way as surrounding traffic. The car was equipped with a Navman MiVue 388 dashboard camera which visually recorded the traffic ahead and on either side and continuously recorded the car's GPS position. This latter provision permitted precise position-time traces of the vehicle to be obtained. These were readily converted into speed-time and acceleration-time traces for the floating vehicle which could be fed into the SIDRA TRIP[29] vehicle operating cost algorithm. The floating car also allowed check estimates to be made of the end of the queue in each lane.

Traffic results

One finding was that truck usage of the study route was very low in the AM peak, with heavy vehicles comprising less than 4% of the traffic. Truck operators obviously planned their schedules to avoid the long queues, although the route is not a major route for truck traffic at any time.

The observations of the back of queue indicate a high level of congestion for westbound through traffic during the AM peak period at the intersection of Wellington Street and Alexandra Parade. Vehicles were spending at least 15 minutes in the entry queue, travelling at about 10 km/h. The SIDRA-based estimated 95th percentile back of queue values for westbound lanes for the 7.45 - 8.00 AM peak period were 2.9 to 3.3 km which was close to the value of 3.5 km observed during surveys conducted using floating car surveys with GPS video equipment on the same section. The SIDRA analysis assumed equal lane utilisation which would tend to underestimate queue lengths. It was evident from the VicRoads data that there was also congestion well before and after the study period.

These results come from a very preliminary and incomplete study. However, the basic observation of queues about 3 km long and taking up to 20 minutes to traverse remain a matter of daily week-day observation for motorist using the Freeway in the AM peak. Taking the value of time as $1/minute suggests that a 15 minute traverse represents a congestion cost of $15 for one AM trip. It was mentioned earlier that total car operating costs are about $0.5 per kilometre, so the operating costs within the queue are about $1.5, or an order of magnitude less than the time cost. This is a core point to emerge from this review and the preliminary study – for most purposes a realistic, easy to measure, lower-bound estimate of the cost of congestion can be obtained by measuring queue lengths at entry points. To this can be added the earlier assessment that the cost of each congested (overflow) intersection within the system to a driver would be about $2. Thus a knowledge of traffic flows on particular routes could lead readily to useful and realistic lower bound estimates for the cost of congestion on that route.

Cost of congestion

Using the data provided by the SIDRA model described above gives the operating costs shown in Fig. 3. Value of time costs accounted for over 75% of these costs.

The 11 am case value of 8 M$/y could be taken as the pre-congestion operating cost of the study area. Thus the 6 am congestion cost would be (14 – 8 = 6) M$/y and the peak congestion cost would be 34 – 8 = 26 M$/y. Linearly interpolating from these three points gives an approximate AM congestion cost as about 70 M$/y.

The relevant Infrastructure Australia report[30] gives the congestion cost for the since-abandoned East-West Link project (which extended west of Nicholson St into areas with much smaller queue storage capacity) as 73 M$/y in 2011 to 144 M$/y in 2031 and a linear interpolation to 2014 would suggest 90 M$/y which is of the same order as the 70 M$/y estimated above.

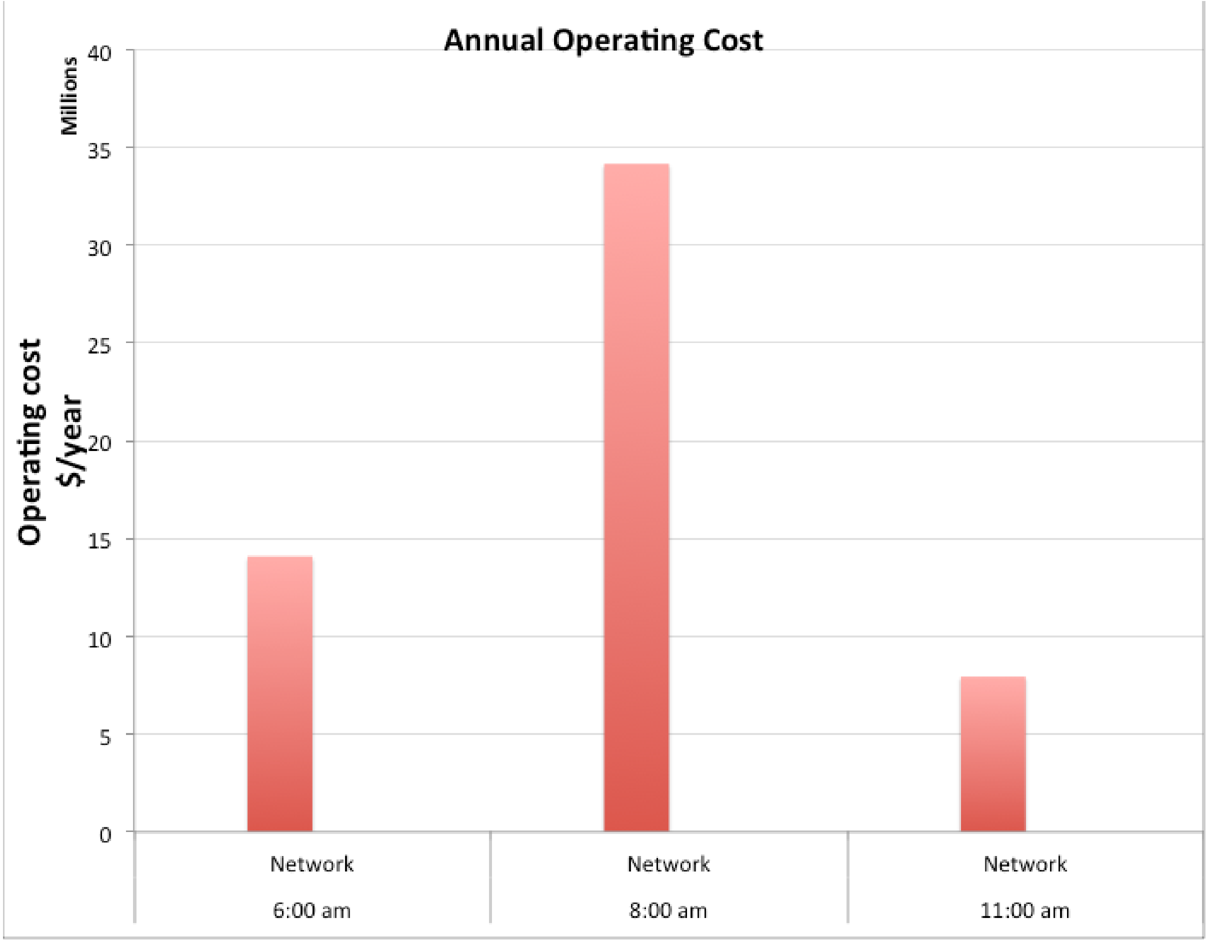

Fig. 3 Preliminary estimated vehicle operating costs in the study area

If this part of the eastern approach to Melbourne represented a tenth of Melbourne's congested road network, then it would put Melbourne's congestion cost at about 700 M$/y compared with the IA/Veitch and Lister 4000 M$/y.

A simple method for assessing congestion costs

As a first approximation to the cost of congestion it is possible to rely on the dominance of the cost of time spent in queues in calculating the total cost of congestion. This dominance means that useful lower bound estimates can be based on the time spent in dominant peak hour queues.

At the simplest level, the VicRoads AADT for the study route at that time was 55 000 vehicles. One could take 30 000 as the AM contribution and then 20 000 as the AM daily traffic during the congested period. If observations suggest a 3 km queue moving at 10 km/h, then the time spent the queue would be about 20 minutes. At $1/minute this leads to a daily congestion cost of $20x1x20,000 and, at 200 working days a year, an annual congestion cost of $20x20,000x200 = 80 M$/y. Note that in the PM period there is no significant congestion on the freeway.

This very simply obtained estimate is very similar to the annual estimates of M$ 70 and 90 given above. Furthermore it could be readily refined to give more accurate cost estimates in real-time using existing VicRoads sensors and cameras recording traffic flow and queue lengths.

The approach could also be extended to intersections within the system by visually (or automatically via SCATS) detecting any signalised intersections where traffic was delayed by more than a signal cycle. At a simple level, the congestion cost would be the number of vehicles so delayed multiplied by the total time taken to pass through the intersection (less one cycle to allow for the inherent delay at that intersection). More precise calculations of high cost intersections could be done using tools like the SIDRA INTERSECTION software.

The effort in doing these calculations would be insignificant compared with the billion dollar costs associated with building planned projects aimed at alleviating congestion. The predictions would not only be more realistic than those given by current broad-brush methods used by planners but could also be used to guide day-to-day traffic management decisions.

Summary of key findings

- Some claimed instances of traffic congestion are merely consequences the normal uncongested operation of an urban traffic system.
- The study of traffic on a heavily congested urban route has shown that traffic congestion was not chaotic but behaved in a manner consistent with traffic engineering principles.
- The prevalence of congestion can be modelled and measured and the cost of congestion calculated in a rational and realistic way. These calculations can be done at varying levels of sophistication, depending on the accuracy needed in a particular circumstance.
- It is important to consider the congestion associated with entry points to conventional grid-based urban traffic systems as a different process to congestion at intersections within the grid.

- It was shown that it is possible and sometimes essential to bring in on-line data from major external sources beyond the signalised intersections being studied. This particularly applies to high demand situations.
- Field measurements partially validated the model predictions and emphasised some critical issues that must be carefully managed. These issues included assigning appropriate values to saturation flows and accounting for lane blockages.
- The potential blocking effect of turning vehicles and of spillback queues from the immediate downstream intersection highlighted the importance in congestion studies of considering downstream intersections.
- This research study showed the importance of identifying the actual demand flows (rather than using stop-line volume counts representing capacity conditions) in modelling congested intersections and networks.
- The study produced a realistic and defendable cost of congestion estimated directly for specific network conditions – and to author's knowledge this has not previously been achieved elsewhere.
- The broad estimate from this study is that the cost of congestion on this sub-link was about M$80 /year, which appears consistent with previous broad-brush estimates.
- The cost of congestion was shown to be dominated by the assumed value of time, as assigned to each vehicle-cum-occupant. This time value is a far more subjective measure than any of the other variables involved, such as the cost of fuel.
- The work showed that even the cost of operating a non-congested traffic system is significant at about 20% of the congested cost. In public terms, this is still quite high.
- A simple method was proposed for giving meaningful and quick lower-bound estimates of the cost of congestion. Another advantage of the method is that the components of the congestion cost can be readily understood by people who are not experts in the underlying technologies.

Acknowledgements

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