

Estimating the Benefits of Trip Time Reliability

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ABSTRACT

There is increasing interest in improving travel time reliability in New Zealand (NZ) and elsewhere, as traffic congestion increases and users find their trip times become less predictable. NZ has adopted a method for estimating the benefit of an improvement in trip time reliability and incorporating that benefit in the economic appraisal of transport projects. The method entails estimating the change in the standard deviation of trip time for each portion of a trip, and assumes that the travel time for each portion of a trip is statistically independent of the travel times for other portions of the trip.

This paper describes a study of travel times on the 11.9 km long eastern section of the Central Circular Route, which is part of the Tokyo Metropolitan Expressway system. The study involved dividing the section of expressway into 39 'links' and collecting the flow rates and speeds on each 'link' on 93 days. Analysis of the data reveals that the travel time for each 'link' (or trip portion) is correlated with (i.e. is statistically dependent upon) the travel times for other trip portions. It is shown that ignoring this correlation results in substantial over-estimation of the benefits of reducing the standard deviation of the travel time for individual trip portions.

INTRODUCTION

The economies in developed countries depend heavily on their transport systems, and that dependence is increasing due to the adoption of 'just-in-time' production methods, which involve reducing the costs associated with holding a goods in stock and relying on required goods being delivered promptly once ordered. This has meant an increased dependence upon a high quality transport service. Surveys of transportation system users (Parkhurst et al., 1992) showed that while the quality of transport services embraces a wide range of service attributes, one of the most important is reliability. They found that users commonly mentioned unreliability, and the consequent variability and unpredictability of travel times, as a negative service attribute.

The increasing awareness of the importance of transport service reliability has led to increased efforts to mitigate the impacts of disruption of road transport networks and to develop methods for including changes in reliability within economic appraisals of road network improvement proposals.

Nicholson and Du (1997) suggest unreliability can be considered to arise from two distinctly different sources; demand (or flow) variations, such as day-to-day variations in the number of vehicle trips, and supply (or capacity) variations, such as capacity reductions due to lane blockages as a result of vehicle breakdowns. Figure 1 shows that for an arc (a link in the road network) with capacity x_{a0} , the travel time varies as a result of arc flow variation. The travel time varies about t_{a2} (corresponding to an arc flow $v_a=v_{a2}$), between a lower bound t_{a3} (corresponding to the lower bound arc flow v_{a3}) and an upper bound t_{a1} (corresponding to the upper bound arc flow v_{a1}). Figure 2 shows that for an arc with flow v_a^* , the travel time varies as a result of arc capacity variation. The travel time again varies about t_{a2} (corresponding to

an arc capacity $x_a=x_{a1}$), between a lower bound t_{a3} (corresponding to the upper bound arc capacity x_{a0}) and an upper bound t_{a1} (corresponding to the lower bound arc capacity x_{a2}).

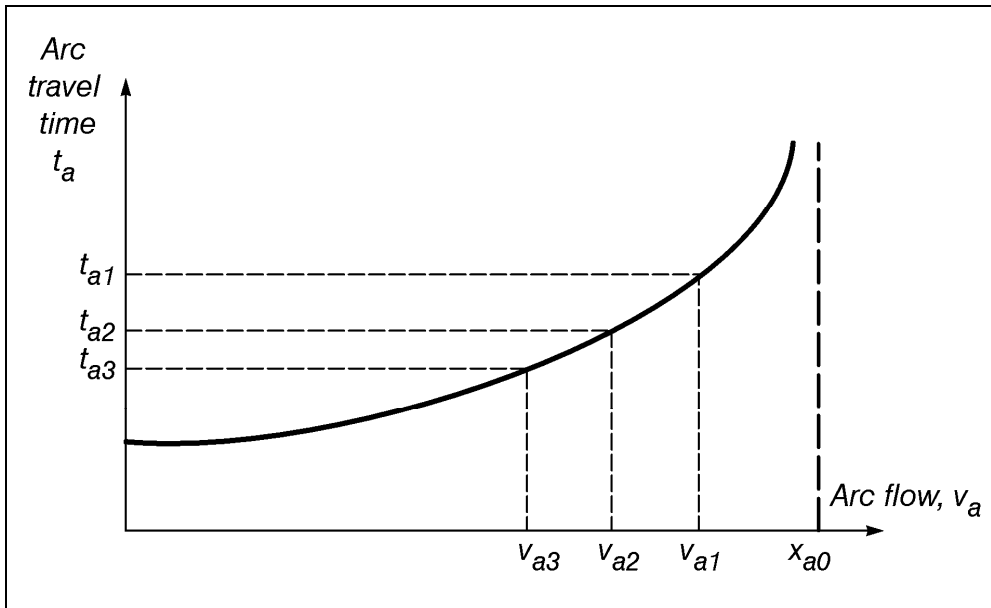


Figure 1: Arc (or Link) Flow Variation

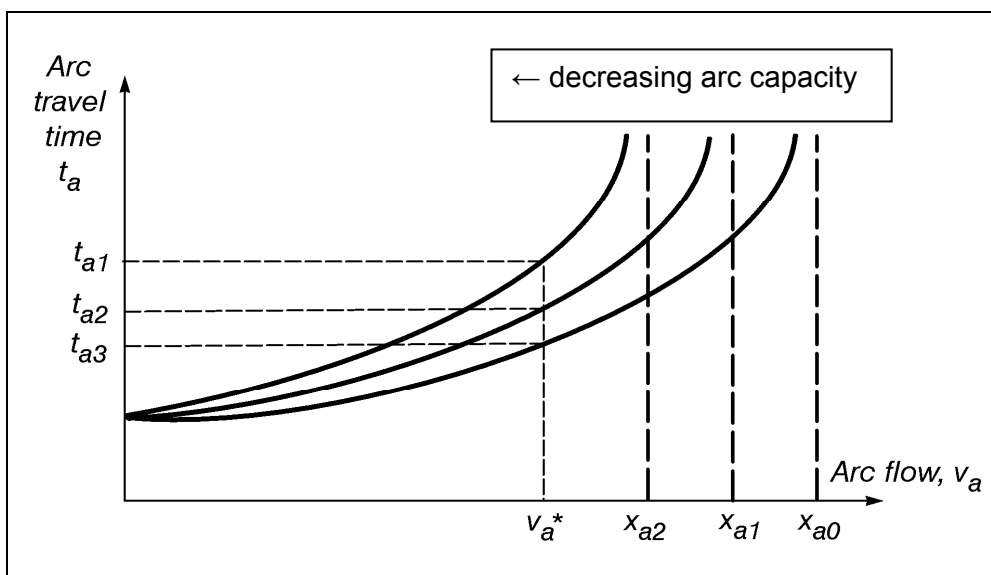


Figure 2: Arc (or Link) Capacity Variation

In reality, travel time variation can arise from either or both sources, and it is not always an easy matter to identify the separate effects of flow and capacity variations. For instance, if an accident occurs during the early part of a peak period and results in a road being partly blocked, it may well be difficult to separate the effect of the capacity reduction and the increasing traffic flow. In major urban areas, where the networks are typically dense and congested, both supply and demand variations occur, and while such variations are typically of relatively short duration, the social and economic impacts can be substantial (Nicholson, 2007). In rural areas, however, where the networks are typically sparse and uncongested, demand variations are generally not important, but supply variations, which can well be of relatively long duration, can have substantial social and economic impacts (Nicholson, 2007). The main focus of transportation network reliability research has been upon reducing the

impact of arc capacity variations. This is probably because there are authorities that are responsible for managing transportation networks and are expected to minimise the frequency and consequence of such events. Travel time variations associated with variations in travel demand are the result of decisions made by many individual travellers, and are thus less amenable to reduction via direct intervention.

A study for the UK Department of Transport (SACTRA, 1999) concluded that ignoring the effect of travel time variability led to the economic benefits of trunk road projects being underestimated by between 5% and 50%. A subsequent UK study (Eddington, 2006) also stressed the importance of accounting for the reliability of travel time. Nevertheless, it has been noted (de Jong et al., 2009) that while major transport infrastructure projects are commonly assessed using cost-benefit analysis, “changes in the reliability of travel time are not incorporated in standard appraisals ... in The Netherlands or in other countries”. In fact, a method for doing this have been included in the economic evaluation procedure in NZ for about five years (Transfund NZ, 2004), but we are perhaps the only country which does take account of travel time reliability in the economic appraisal of transport infrastructure projects.

VALUATION OF TRAVEL TIME RELIABILITY CHANGES

The current NZ appraisal procedure (NZTA, 2008) allows for “the unpredictable variations in trip times, which are experienced for a trip undertaken at broadly the same time every day” (i.e. “day-to-day variations in traffic congestion, typically as a result of day-to-day variations in flow”). The procedure allows for reliability associated with demand variations only, and “does not account for the delays that may result from major incidents on the road network” (i.e. incidents involving supply variations).

It should also be noted that the procedure does not estimate variations in the travel times of individual travellers, but estimates the variation in the mean travel times. The latter can be substantially less than the former, especially for periods with low flow rates, when there can be considerable variability in the travel times of individual users, because the lack of traffic congestion means a lack of constraint on user speed choice.

The procedure involves using the standard deviation of travel time (s) as the measure of travel time variability. It is assumed that the standard deviation of travel time is related to the ratio of the volume (v) to the capacity (c) according to the following sigmoid-shaped relationship:

$$s = s_{min} + \frac{(s_{max} - s_{min})}{1 + \exp[b(\frac{v}{c}) - a]}$$

where s_{min} is the minimum standard deviation of travel time (when v equals zero) and s_{max} is the maximum standard deviation of travel time (when v equals c), and a and b are constants. The values of s_{min} , s_{max} , a and b vary according to the type of facility (e.g. motorway, urban arterial, rural highway, signalised intersection, unsignalised intersection).

It has been shown (Ensor, 2004) that the above relationship for the standard deviation of the travel time implies that the standard deviation:

- increases only gradually from zero as v increases from zero to about $0.85ac$;
- increases rapidly as v increases from about $0.85ac$ to about $1.15ac$;
- equals $[(s_{min} + s_{max})/2]$ when v equals ac ;
- increases gradually towards s_{max} as v increases above about $1.15ac$.

The use of the standard deviation of travelling time as the measure of reliability has the advantage that the units are the same as the units of travelling time, and the appraisal procedure (NZTA, 2008) values a one minute reduction in the standard deviation of travel

time at 0.8 and 1.3 times the value of a one minute reduction in the travel time, for cars and commercial vehicles respectively. The value for cars is identical to the RAND Europe (2004) recommendation for cars, while the value for commercial vehicles is slightly greater than the 1.24 recently recommended by de Jong et al. (2009).

RAND Europe (2004) and de Jong (2009) recommend, for urban and inter-urban public transport users, that a one minute reduction in the standard deviation of travel time be valued at 1.4 times the value of a one minute reduction in the travel time. This implies that reliability is particularly important for public transport users, and suggests that the NZ procedure (NZTA, 2008) is deficient in not including any method for valuing improvements in travel time reliability for public transport.

ESTIMATION OF TRAVEL TIME RELIABILITY CHANGES

The NZ procedure (NZTA, 2008) allows the valuation of a reduction in the mean and/or standard deviation of the travel time for part of a trip. This is a straight-forward task for improvements in the mean travel time, because the travel time for a trip is simply the sum of the travel times for the segments of the trip, and one can place a value on a reduction in the mean travel time for one segment of a trip, without knowledge of the mean travel times for the other segments. It is not, however, a straight-forward task for improvements in the standard deviation, even when the travel times for the segments are independent.

In this case, the standard deviation of travel time for a trip cannot be obtained by summing the standard deviations for the segments of the trip. Instead, one must sum the variances of the travel times for the segments of the trip, and calculate the standard deviation of the trip travel time as the square root of the sum of the variances of the segment travel times. Hence, one cannot place a value on a reduction in the standard deviation of the travel time for one segment of a trip (e.g. changing the form of control at an intersection), without knowledge of the variability of travel times for the other segments.

As noted by Nicholson (2007), it can be shown that the standard deviation of the trip travel time is less than the sum of the standard deviations of the segment travel times, and the discrepancy between the two quantities increases as the number of segments with unpredictable travel time increases. Hence an $x\%$ reduction in the standard deviation for one segment will mean a smaller than $x\%$ reduction in the standard deviation for the complete trip (i.e. the change in trip travel time reliability will be over-estimated), and the degree of over-estimation will increase as the number of segments (i.e. the trip length) increases.

The economic appraisal procedure (NZTA, 2008) allows for this in an 'ad hoc' manner, by multiplying the value of a reduction in the standard deviation of travel time for part of the trip by a factor, which varies from 100% for regional models to 50% for corridor models to 30% for intersections and individual passing lanes.

It can be shown (Mood et al., 1974) that for a trip involving n segments, where the travel time for the i^{th} segment is a random variable X_i , with mean μ_i and standard deviation σ_i , and the segment travel times might not be independent, the expected total trip time is

$$\mu_T = \sum_{i=1}^n \mu_i$$

and the variance of the total trip time is

$$\sigma_T^2 = \sum_{i=1}^n \sigma_i^2 + 2 \sum_{i=1}^{n-1} \sum_{j=i+1}^n \rho_{ij} \sigma_i \sigma_j$$

where ρ_{ij} is the correlation coefficient of the two random variables X_i and X_j .

Each correlation coefficient ρ_{ij} must all lie in the range (-1, +1), and will be:

- zero when X_i and X_j are independent or not correlated;
- positive when X_i and X_j are positively correlated, that is, X_j tends to be more/less than its mean μ_j when X_i is more/less than its mean μ_i ;
- negative when X_i and X_j are negatively correlated, that is, X_j tends to be less/more than its mean μ_j when X_i is more/less than its mean μ_i .

It is likely that the travel time for all segments will be greater than the mean value, if this is based on average traffic conditions, at times when the road network is fairly uniformly congested (i.e. the travel times for the segments will be positively correlated). For a road network which is subject to congestion at particular locations only (e.g. bottlenecks), the correlations between the travel times for the segments on opposite sides of the bottlenecks might be negatively correlated.

It can be seen that the variance of the total trip time comprises two terms:

- the sum of the variances of the segment travel times (the 'variance term');
- the sum of the products of the correlation and standard deviations (the 'correlation term').

The method for estimating the trip time variance in the NZ economic appraisal procedure (NZTA, 2004) involves only the 'variance term'. That is, the 'correlation term' is ignored or assumed to be negligible.

As noted by Nicholson (2007), the 'correlation term' can be ignored or assumed to be negligible if and only if:

- the correlations of the travel times for the segments are all zero (i.e. the segment travel times are independent), or
- the standard deviations of the segment travel times are all zero (i.e. there is no variation from day to day in the segment travel times), or
- there are positive and negative correlations of such magnitudes that the products of the correlations and standard deviations cancel completely.

It is very unlikely that any of these three conditions will be satisfied in practice. That is, it is very unlikely that the variance of the total trip time will equal the sum of the variances of the segment travel times, as assumed in the NZ economic appraisal procedure.

In the absence of empirical data regarding the variances and correlations, one might assume that the variances of the segment travel times are all equal to σ^2 , say, and that the correlations ρ_{ij} ($i \neq j$) are all equal to ρ , say. Nicholson (2007) noted that in this case, the variance of the total trip time is

$$\sigma_T^2 = n\sigma^2 + n(n-1)\rho\sigma^2.$$

It can be seen that the 'covariance term' depends linearly on ρ , but depends upon the square of σ and the square of n (i.e. the error is particularly sensitive to the values of σ and n). Hence, the 'covariance term' might be quite substantial when σ or n is large, and very substantial when both σ and n are large. That is, where the variance of the travel time for individual segments is large and/or trips are long and are sensibly considered to comprise a large number of segments, the assumption of independence (i.e. ignoring the 'covariance term') could lead to a large error in the estimate of the variance of the total trip time.

The importance of considering and allowing for correlation (i.e. not assuming independence) when considering transport network reliability issues has been noted previously by Du and Nicholson (1997) and Dalziell and Metcalfe (2005).

ESTIMATION OF CORRELATION

In an effort to identify the nature and extent of correlation between the travel times for segments of trips, a study of travel times on the 11.9 km long eastern section of the Central Circular Route, which is part of the Tokyo Metropolitan Expressway system, was undertaken (see Figure 3). The north-bound carriageway, from the Horikiri junction to Kasai junction, was studied. The curve radii exceed 1600 m and the gradients are less than 3%, except for a short section near the Kasai junction, where there is a curve with a radius of 320 m and a gradient of about 4.1%.

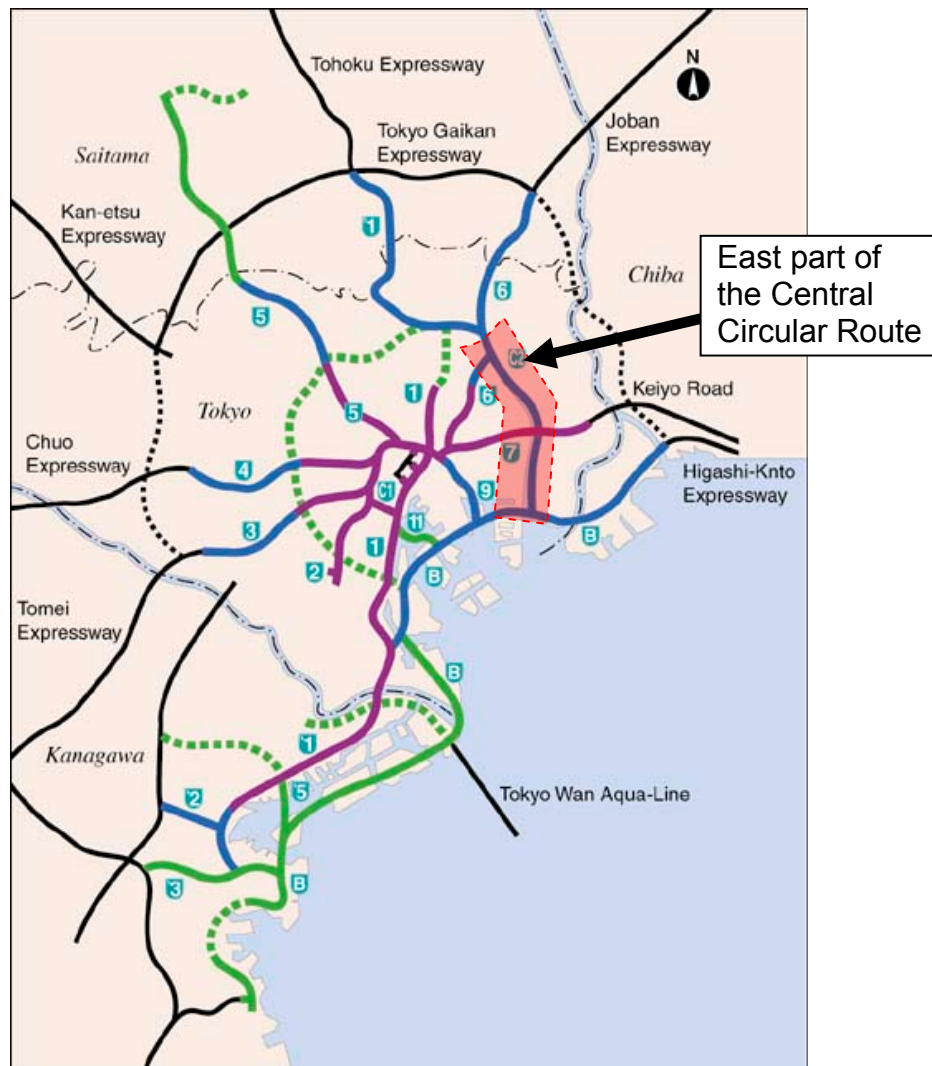


Figure 3: Study Area

The study (Munakata, 2007) involved dividing the section of expressway into 39 links and collecting the flow rates and speeds on each link on 93 days. The links boundaries were defined to be the mid-points between the flow rate and speed detectors, which are located at approximately 300 metre spacing along the eastern section of the Central Circular Route. The link locations and lengths (in kilometres), along with the locations of entry and exit ramps, are shown in Figure 4. It can be seen that the link lengths varied between 200 and 420 metres, with the vast majority being within the range 300 ± 50 metres.

The flow rate and speed at the mid-point of each link was assumed to represent the flow rate and speed for that link. The flow rate and speed were collected at intervals of one minute,

with the link travel times being calculated from the link lengths and link speeds. This enabled the estimation of correlation between travel times on links as users travelled along the 11.9 km length, allowing for the speed of travel along the length of expressway, as well as the estimation of the correlations between link travel times at instants in time.

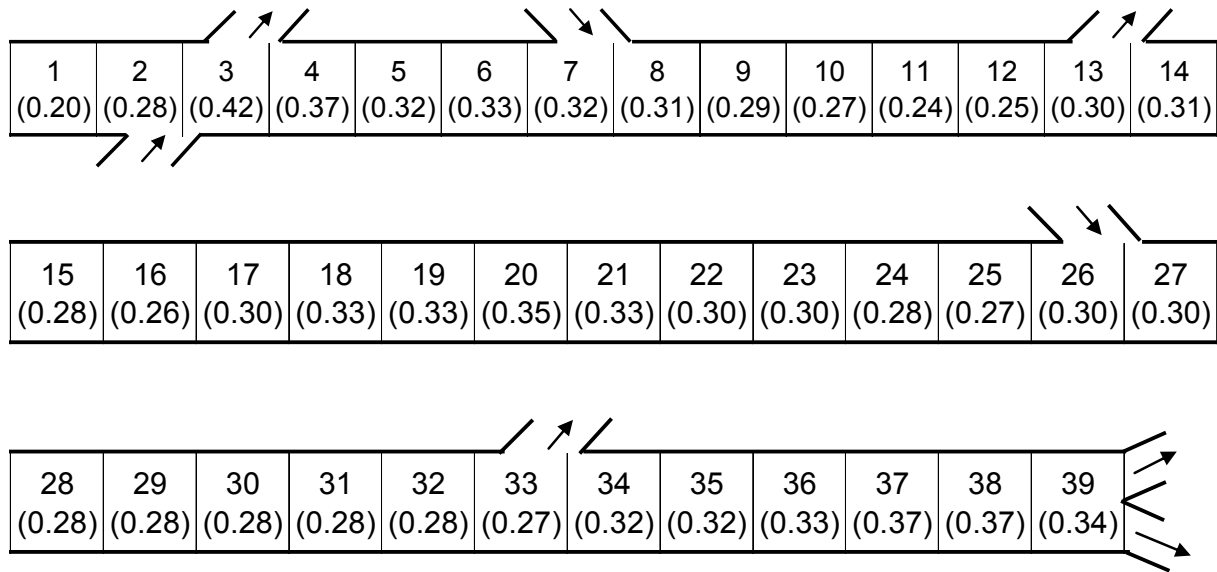


Figure 4: Link Numbers and Link Lengths

The former (or trip-based approach) involves identifying the correlation between link travel times spread over several one-minute intervals, while the latter (or instantaneous approach) involves identifying the correlation between link travel times during particular one-minute intervals (see Figure 5). The former correlations are more relevant than the latter, as users do not travel along such a length of expressway in an instant. Both methods were used, to identify how the results for the two methods might differ.

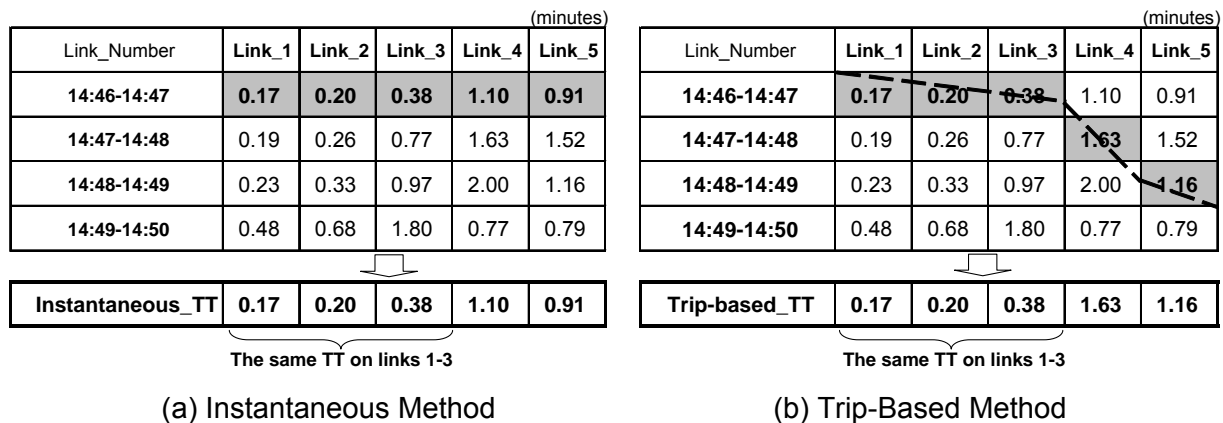


Figure 5: Comparison of Instantaneous and Trip-Based Analyses

Analyses were undertaken for aggregations of links, as shown in Figure 6, in order to assess the sensitivity of the results to changes in the length of 'analysis units'.

The daily flow rate varied a little between sections (i.e. the lengths between ramps), but was generally in the range from 25 to 27 thousand vehicles/day/lane, with about 66% occurring in the period from 7am to 7pm and about 7% occurring in the highest-flow hour (from 9am to 10am), and with about 65% and 35% of the traffic being cars and trucks, respectively.

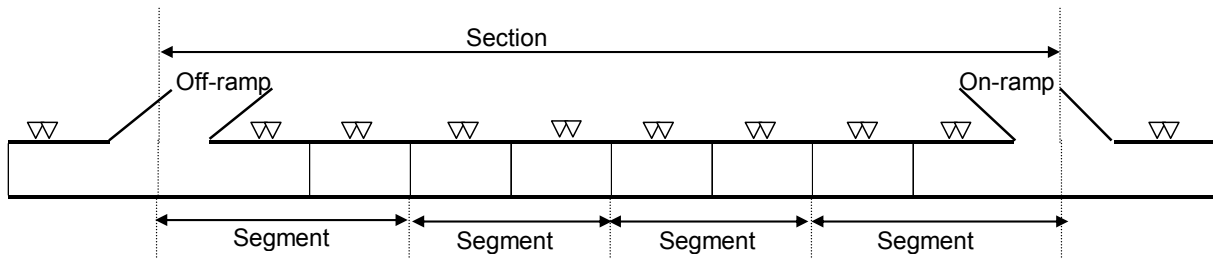


Figure 6: Example of segments and a section

RESULTS AND DISCUSSION

The average, maximum and minimum correlation coefficients are shown in Tables 1 and 2, for the peak and off-peak periods. Tables 1 and 2 also show the sample sizes and the corresponding critical values of the correlation coefficient (95% confidence level).

	All Days	Weekdays	Sundays & National Holidays	Wednesdays
Sample Size	93	60	20	12
Critical Coefficient	0.205	0.250	0.4438	0.576
Instantaneous Method				
Average	0.473	0.362	0.647	0.265
Maximum	0.974	0.974	0.979	0.997
Minimum	-0.005	-0.166	0.075	-0.671
Trip-Based Method				
Average	0.463	0.362	0.647	0.274
Maximum	0.957	0.987	0.985	0.983
Minimum	0.039	-0.094	0.144	-0.697

Table 1: Summary of Correlation Coefficients (Links in Peak)

	All Days	Weekdays	Sundays & National Holidays	Wednesdays
Sample Size	93	60	20	12
Critical Coefficient	0.205	0.250	0.4438	0.576
Instantaneous Method				
Average	0.471	0.431	0.470	0.369
Maximum	0.981	0.982	0.993	0.997
Minimum	-0.024	-0.112	-0.491	-0.642
Trip-Based Method				
Average	0.488	0.442	0.621	0.264
Maximum	0.986	0.987	0.994	0.996
Minimum	-0.006	-0.115	0.000	-0.496

Table 2: Summary of Correlation Coefficients (Links in Off-Peak)

It can be seen that the average correlation coefficients for 'weekdays', 'Sundays and national holidays', and 'all days' exceed the critical values, indicating that the correlation is statistically significant. Although the average correlation coefficients are substantial for 'Wednesdays', the sample sizes are such that they are not statistically significant. It can also be seen that the correlation coefficients vary considerably, from values a little less than +1 to about -0.7. The high correlations are generally for pairs of links that are close together, and the correlations between link travel times generally decline as the distance between the links increases. It is interesting that some negative correlations have been observed, suggesting

the existence of 'bottlenecks' on the eastern section of the Central Circular Route (northbound).

Tables 3 and 4 show the corresponding contributions of the components of the total variance (i.e. the sum of the variances and the sum of the product of the correlations and standard deviations), for the peak and off-peak periods. It can be seen that the sum of the link travel time variances (the 'variance term') amounts to only about 9% of the total variance. That is, the sum of the products of the correlation and link travel times standard deviations (the 'correlation term'), which is omitted when it is assumed that link travel times are independent (as is done in the NZ economic appraisal procedure), is generally about ten times greater.

	All Days	Weekdays	Sundays & National Holidays	Wednesdays
Instantaneous Method				
Variance term	0.29 (7%)	0.36 (10%)	0.03 (5%)	0.10 (13%)
Correlation term	3.61 (93%)	3.30 (90%)	0.57 (95%)	0.69 (87%)
Total	3.90	3.66	0.60	0.79
Trip-Based Method				
Variance term	0.32 (7%)	0.35 (9%)	0.03 (5%)	0.09 (12%)
Correlation term	4.25 (93%)	3.60 (91%)	0.60 (95%)	0.67 (88%)
Total	4.57	3.95	0.63	0.76

Table 3: Summary of Variance Components (Links in Peak)

	All Days	Weekdays	Sundays & National Holidays	Wednesdays
Instantaneous Method				
Variance term	3.28 (8%)	4.56 (9%)	0.43 (9%)	7.02 (8%)
Correlation term	40.37 (92%)	47.62 (91%)	4.22 (91%)	82.43 (92%)
Total	43.75	52.18	4.65	89.45
Trip-Based Method				
Variance term	3.43 (9%)	4.64 (11%)	0.47 (9%)	11.01 (13%)
Correlation term	33.67 (91%)	37.60 (89%)	4.60 (91%)	74.69 (87%)
Total	37.10	42.24	5.07	85.70

Table 4: Summary of Variance Components (Links in Off-Peak)

This means that if one is doing an economic appraisal of a project which will reduce the sum of the link travel time variances by 50%, say, then the total variance might be reduced by only about 5%, unless the project also reduces the other component of variance by 50%. This is very unlikely to be the case, because this would involve making changes to all links (to reduce the correlation and/or the standard deviation). This suggests that projects which have a small effect of the correlation-related component might well have a greater effect on the total variance than projects which have a large effect on one link-specific variance term. That is, 'route treatments' might be a more productive approach to improving trip time reliability than 'site treatments'. The former are likely, however, to be much more expensive.

It can be seen from Tables 1 and 2 that the correlation coefficients for the peak and off-peak periods are fairly similar. However, Tables 3 and 4 show that the total variance in travel time is distinctly higher for the off-peak period than for the peak period. It can also be seen that the differences in the results for the 'instantaneous method' and 'trip-based method' are fairly similar. It should be noted that analyses at the 'segment' level (see Figure 6) reveal that the results are not sensitive to the level of spatial aggregation (Munakata, 2007).

Although this study has used travel time data for the Tokyo Metropolitan Expressway system, there is no obvious reason why a study of the Auckland Motorway system (or indeed any other motorway system) should produce very different results.

CONCLUSION

The research results show that there is a need to review and revise the approach currently incorporated in the NZ economic appraisal procedures (NZTA, 2008) for estimating the benefits of improvements in travel time reliability, to include consideration of the effect of correlation (or non-independence) of travel times on different portions of trips. Otherwise, the benefits are likely to be over-estimated considerably.

The value of using economic appraisal procedures depends strongly on the quality of the process for identifying options for appraisal. Hence, there would be value in investigating how to identify and develop projects which address the total travel time variance, and not just a small portion of that variance. This might mean a greater emphasis on 'route treatments' rather than 'site treatments'.

In addition, it would be appropriate to consider including in the procedure a value for an improvement in the standard deviation of travel time for public transport users.

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