ESTIMATING THE TRAVEL TIME RELIABILITY BENEFITS OF PROJECTS

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ABSTRACT

The economies in developed countries depend heavily on their transport systems. That dependence has increased with the adoption of 'just-in-time' production methods, which involve reducing the costs associated with holding goods in stock and relying on required goods being delivered promptly once ordered. This has meant an increased emphasis on the reliability of the service and increased efforts to mitigate the impacts of disruption of road transport networks, and has led to changes in reliability being included within economic appraisals of road network improvement projects that are expected to result in an improvement in reliability.

Current methods for estimating the benefits of such projects typically involve estimating the change in the standard deviation of trip time and assigning a monetary value to that reduction. While it can be shown that the estimate of the standard deviation of trip time is sensitive to correlation between the travel speeds on the segments of a trip, the methods do not allow for such correlation. The few studies to assess the level and extent of such correlation have led to different conclusions regarding the need to allow for such correlation. This paper will discuss why those studies have produced different conclusions.

Another issue associated with estimating the travel time reliability benefits of projects is that current traffic assignment methods do not take account of travel time variability when predicting the flows on alternative paths through networks. This means inconsistency between the flow estimation and economic appraisal stages, and casts further doubt upon the robustness of estimates of the travel time reliability benefits of road network improvement projects.

The paper will review research relating to these two issues and describe research which shows that ignoring correlation can result in substantial errors in estimates of the benefits of projects that are expected to result in an improvement in reliability. The paper will conclude with a discussion of how the process for estimating travel time reliability benefits can be improved.

Keywords: travel time, reliability, estimation, benefits, correlation.

INTRODUCTION

The economies in developed countries depend heavily on their transport systems. That dependence is increasing due to the adoption of 'just-in-time' production methods, which involve reducing the costs associated with holding 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. While the quality of transport services embraces a wide range of service attributes, surveys of transport system users, such as that by Parkhurst et al. (1992) and Bates et al. (2001), have shown that 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 an increase in efforts to mitigate the impacts of disruption of road transport networks, especially variability in travel times, and to develop methods for including the benefits of reductions in travel time variability within economic appraisals of road network improvement proposals. 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 under-estimated by between 5% and 50%. A method for including the economic benefits of reducing travel time variations was first included within the New Zealand (NZ) economic appraisal procedure in 2004 (Transfund NZ, 2004). A subsequent UK study (Eddington, 2006) also stressed the importance of accounting for the reliability of travel time, and methods for doing this are well-established in the UK (Department for Transport, 2009 & 2012). This paper examines whether the methods for estimating the benefits of reducing travel time variations are sound.

MODELLING TRAVEL TIME VARIABILITY

There are two basic approaches to assessing travel time reliability. In both approaches the value of reducing variation in travel time is combined in an expected utility model with the value of saving travel time, so the value of travel time variability is directly linked to the value of travel time saving.

The first is the 'scheduling' approach, which is based on the work of Small (1982). In this approach, travellers are assumed to have a preferred arrival time (PAT) at their destination and to choose the departure time (t_o), allowing for the travel time T being a function of the departure time, i.e. $T = T(t_o)$, so as to maximise the expected utility

$$E[U] = \alpha.\ E[T] + \beta.\ E[SDE] + \gamma.\ E[SDL] + \delta.\ E[L] \qquad (1)$$

where $E[T]$ = expected travel time;
SDE = $\max\{0, PAT - [t_o + T(t_o)]\}$ (i.e. the schedule delay early);
SDL = $\max\{0, [t_o + T(t_o)] - PAT\}$ (i.e. the schedule delay late);
L = 1 if SDL > 0 and 0 otherwise (i.e. a dummy variable for being late);
α = the disutility per unit of travel time;
β = the disutility per unit of early arrival;
γ = the disutility per unit of late arrival;
δ = the disutility of arriving late.

α, β, γ and δ are all ≤ 0.

It has been shown (Bates, 2001) that the scheduling approach can be simplified, giving the 'mean/variance' approach, which assumes that there is a direct trade-off between changes in the mean travel time and some measure of variation in travel times, such as the variance or standard deviation. As noted by the Department for Transport (2009), the sum of the second and third terms in the expression for the expected utility is closely related to the standard deviation of travel time, provided travellers can optimise their choice of departure time on a continuous basis, as is the case for trips not involving public transport.

The 'mean/variance' approach, using the standard deviation as the measure of variability, is the commonly used approach, and has been implemented in economic appraisal procedures in some countries, such as New Zealand (Transfund NZ, 2004; NZ Transport Agency, 2010) and the United Kingdom (Department for Transport, 2009 and 2012). With this approach, the expected utility (E[U]) is a linear combination of the expected travel time and the standard deviation (σ) of travel time, i.e.

$$E[U] = \alpha.\ E[T] + \lambda.\sigma \quad (2)$$

where λ = the disutility per unit of standard deviation of travel time.

The ratio λ/α is commonly referred to as the 'reliability ratio', and it reflects the relative utilities of reductions in the standard deviation of the trip time and the expected trip time. The Department for Transport (2009) specifies that the ratio is 0.6 – 1.5 for public transport and is about 0.8 for cars. The NZ Transport Agency (2010) also specifies a value of 0.8 for cars, while specifying a higher value (1.3) for commercial vehicles, to reflect the growing concern about the impact of travel time variability on business costs. These values accord reasonably well with the recommendations of RAND Europe (2004) and de Jong et al. (2009).

The focus of this paper is on the 'mean/variance' approach, which is the basis of the methods used in NZ and the UK, and the estimation of changes in the standard deviation of travel time

ESTIMATING TRAVEL TIME VARIABILITY

Introduction

Travellers are primarily interested in the variability of the travel times for complete trips, rather than for specific segments of trips. However, many projects involve changing the travel time characteristics (mean and/or standard deviation) of only parts of a route or network. It is this necessary to estimate changes in trip time variability, based on estimates of the changes for parts of trips.

A further complication is that not all trips in a network will entail using those segments for which the travel time variability is likely to change, so not all travellers will benefit equally from the changes. The benefit will depend upon the extent to which the level of demand and pattern of travel in the network will change. It should be noted that some projects will affect trip generation, trip distribution, mode choice and route choice (i.e. the four stages of the traditional sequential demand modelling approach), and methods which ignore these effects, especially the potential for re-routing of traffic, are likely to give inaccurate estimates of the benefits of reducing the travel time variability in part of a network. The need for allowing for re-routing of traffic, and the difficulty associated with doing so, are discussed later.

NZ Economic Appraisal Method

The NZ economic appraisal procedure (NZ Transport Agency, 2010) involves using the standard deviation of travel time (σ) as the measure of travel time variability. It is assumed that the standard deviation of travel time for a segment (i.e. a link or node of the network) is related to the ratio of the volume (v) to the capacity (c) according to the following sigmoid-shaped relationship:

$$\sigma = \sigma_{min} + \frac{(\sigma_{max} - \sigma_{min})}{1 + exp[\,b\{(\frac{v}{c}) - a\}]} \tag{3}$$

where σ_{min} is the lower bound σ (as v/c approaches zero);
σ_{max} is the upper bound σ (as v/c increases above unity);
a and b are constants.

The values of σ_{min}, σ_{max}, a and b vary according to the type of facility (e.g. motorway, urban arterial, rural highway, signalised intersection, unsignalised intersection). The relationship between σ and (v/c) is sigmoid, as shown in Figure 1.

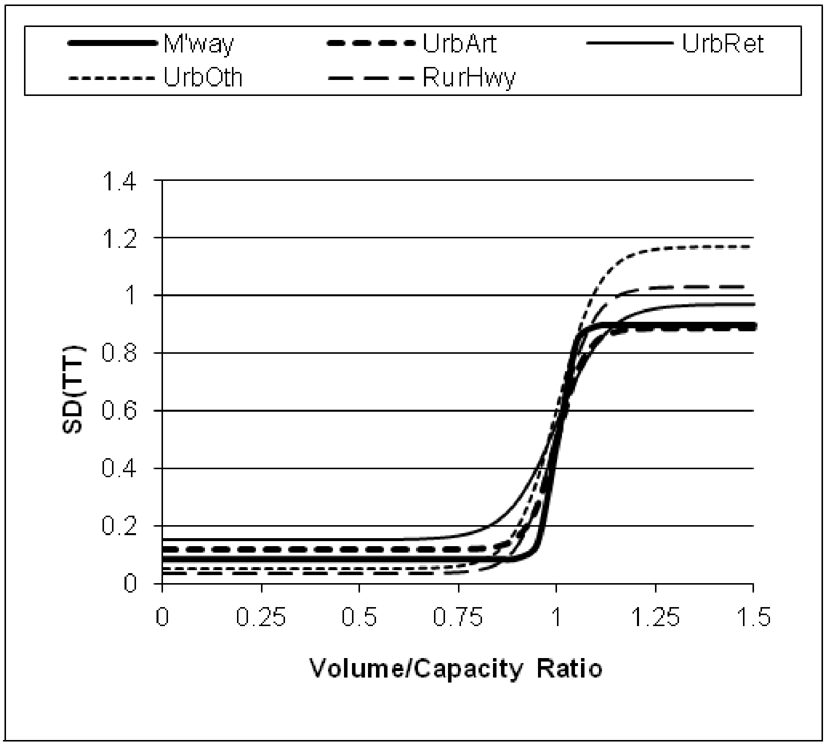

Figure 1 – Relationship between σ and (v/c) for NZ economic appraisal method

The NZ appraisal procedure allows for the fact that projects will generally affect the travel time variability for only some trips and parts of trips, by adjusting the travel time variability benefit by multiplying the calculated variability benefit by the factor shown in Table 1.

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, i.e.

$$\sqrt{(\sigma_1)^2 + (\sigma_2)^2 + ... + (\sigma_n)^2} < \sigma_1 + \sigma_2 + ... + \sigma_n \tag{4}$$

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). The NZ appraisal method involves summing variances over series of links, assuming the travel time on the links are independent.

Table 1 – Factors for adjusting estimating network benefits

Percentage of variance outside of study area	Factor for benefit calculation	Indicative transport network model coverage
<20%	100%	Regional model
20%	90%	Sub-regional model
50%	70%	Area model
75%	50%	Corridor model
90%	30%	Intersection model, individual passing lane

UK Economic Appraisal Methods

The UK has two methods, one for urban roads and the other for inter-urban motorways and dual carriageways.

The change in the standard deviation of travel time on an urban route, as a result of a project, can be estimated as follows (Department for Transport, 2009):

$$\Delta\sigma_{ij} = 0.0018\ (t_{ij1}^{2.02} - t_{ij2}^{2.02})\ /\ d_{ij}^{1.4} \qquad (5)$$

where $\Delta\sigma_{ij}$ = change in standard deviation (seconds);
t_{ij1} = trip time (seconds) before implementation of the project;
t_{ij2} = trip time (seconds) after implementation of the project;
d_{ij} = trip distance from origin i to destination j.

This expression can be used provided that the distances and free-flow speeds do not change as a result of the project.

It is worth noting that this method appears to consider whole trips, and does not explicitly involve assuming that the travel times on a series of links are independent and summing the variances of travel times for those links.

For motorways and dual-carriageway roads, where there is less opportunity for diversion to avoid congestion, the use of the INCA program is recommended (Department for Transport, 2009). According to the INCA user manual (Department for Transport, 2012), the standard deviation of trip time (seconds per km) is given by

$$a + bx + cx^2 + dx^3 \qquad (6)$$

where x = mean trip time per km
a, b, c and d vary with road type.

In some circumstances, this cubic function indicates that variability increases with journey time, reaches a maximum value, then decreases. To avoid a decrease in variability as mean trip time per km increases above the value at which maximum variability occurs, the calculated variability in this ‘decreasing’ region is replaced with the maximum value.

With this method, changes in the standard deviation are calculated from changes in the mean trip times. The INCA program calculates the variance of travel time for each link in a network, and sums the variances for the links comprising user-specified routes through the network. That is, it assumes that the travel times on links are independent.

It should be noted that the route standard deviation calculated by INCA represents the whole journey, and not just that part of it passing through the scheme. INCA requires the base year trips for each route to be specified (i.e. it assumes no change in the level and pattern of demand).

CORRELATION OF TRAVEL TIMES

Introduction

None of the three above-mentioned methods for estimating the standard deviation of trip times make any allowance for correlation of travel times on segments of a trip, despite the emergence of evidence that such correlations can exist in certain circumstances, as discussed below.

It follows from statistical theory (Mood et al., 1974) that for a trip involving n parts, where the travel time for the i-th part is a random variable X_i whose mean is μ_i and standard deviation is σ_i, then the variance of the total trip time is:

$$\sigma_T^2 = \sum_{i=1}^{n} \sigma_i^2 + 2 \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \rho_{ij} \sigma_i \sigma_j \quad (7)$$

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

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

- the sum of the variances of the travel times for the parts of the trip (the 'variance term');
- the sum of the products of the correlation and standard deviations (the 'covariance term').

The covariance term will make a zero contribution to the trip time variance if and only if:

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

As noted by Nicholson (2007), it is very unlikely that any of these three conditions will be satisfied in practice.

The 'variance term' has n components, while the 'covariance term' has $n(n-1)$ components. Nicholson (2007) noted that if the variances of the travel times for the parts of the trip are all equal to σ^2, say, and that the correlations ρ_{ij} (i ≠ j) are all equal to ρ, say, then the variance of the total trip time can be shown to be

$$\sigma_T^2 = n\sigma^2 + n(n-1)\rho\sigma^2 \quad (8)$$

It can be seen that the error associated with ignoring the 'covariance term' increases linearly with an increase in $|\rho|$ and increases quadratically as σ and n increase (i.e. the error is particularly sensitive to the values of σ and n). It can also be seen that the 'covariance term' is negligible if and only if it is very much less than the 'variance term', and this is true if and only if $|\rho|$ is very much less than the inverse of (n-1). This suggests that the inverse of (n-1) might be treated as a 'threshold correlation', such that if the correlation exceeds it, then the error associated with ignoring the 'covariance term' might be substantial.

As n increases, the 'threshold correlation' quickly becomes quite small. Given that a trip can, in theory, be subdivided into an extremely large number of extremely short parts, the 'threshold correlation' can be extremely small. In addition, the correlation between traffic conditions in adjacent parts will invariably increase as the section lengths decrease. However, it is not sensible to divide a trip into extremely short parts, and previous studies of travel time variability that have involved dividing trips into parts have adopted substantial lengths.

Previous Studies of Travel Time Variability

The variability of travel times has been of interest for at least 60 years, with Turner and Wardrop (1951) finding that the distribution of journey times in Central London were not described well by a Normal distribution. A later study (Herman and Lam, 1974) found that the times of journeys to and from work in Detroit were not described well by a Normal distribution, while Richardson and Taylor (1978) found that the travel times of journeys to and from the centre of Melbourne during the morning and evening peak periods were described by a Lognormal distribution better than by a Normal distribution.

The two later studies involved having selected drivers record the travel times for their journeys. As noted by Richardson and Taylor, there is scope for this method to give results which are affected by the driving styles of the selected drivers (e.g. aggressive drivers might have a lower mean travel time, but a higher variability in travel times, than passive drivers). They sought to mitigate the effect by giving drivers some training and testing the results for homogeneity, and found that the results did not vary statistically significantly between drivers. They also specified the route to be driven, thereby eliminating variation due to variations in driver route choice.

Richardson and Taylor (1978) divided the trip into 19 fairly homogeneous sections and recorded the times for each section. The characteristics of the sections varied considerably, with section lengths varying between 0.16 and 1.36 km, and the number of lanes varying between two to six. About half the sections were dual-carriageway roads (some with and some without separate service roads), while the remainder were single-carriageway roads. About half the sections included one set of traffic signals, while the remainder included none. Richardson and Taylor adopted the coefficient of variation as the measure of travel time variability, and the ratio of the actual travel time to the minimum travel time (i.e. the travel time in free-flow conditions) as the measure of congestion (or congestion coefficient). They found that the congestion coefficient varied considerably between the sections (from a little over 1.0 to about 8.3), and found that the travel time variability increased as the level of congestion increased.

Richardson and Taylor also investigated the level of correlation between the travel times on pairs of sections. They had 19 sections, with four samples (with 20 observations in each), giving a total of 684 correlation coefficients. Of those coefficients, about 6.3% and 3.1% were statistically significantly different from zero at the 5% and 1% levels respectively. They considered the 18 consecutive section pairs separately, and found that about 13.9% and 5.6% were statistically significantly different from zero at the 5% and 1% levels respectively. They concluded that "it is reasonable to accept the hypothesis that route section unit travel times (i.e. the travel time per unit distance) were independent".

A more recent study (Eliasson, 2006) involved analysing travel times on streets in and around central Stockholm. Travel times were obtained via a camera system and matching of the number plates of vehicles entering and leaving each of the 84 links, which generally had two lanes in each direction (some had only one), a speed limit of 50 km/h (some had 70 km/h), daily vehicle flows mostly between 15,000 and 50,000 (summing both directions) and quite a few (most often signalled) intersections. Link lengths varied from 0.3 to 5 km, and travel time data were collected for four days (Monday-Thursday) each week during a period of 2.5 months in late 2005. For each link, the mean travel time and the standard deviation of the travel time were obtained for each 15 minute interval period.

Eliasson also found a relationship between travel time variability and the level of congestion (as measured by the ratio of the actual travel time to the free-flow travel time, minus one), with the coefficient of variation tending to increase with increasing congestion up to a certain point, after which it appeared to decrease. He suggested that the decrease for very highly congested conditions reflects the predictably slow travel speeds in such conditions. This is consistent with the relationship (equation 1) between the standard deviation of travel time and the volume/capacity (v/c) ratio; as the v/c ratio increases towards unity, the expected travel time increases more rapidly, the standard deviation increases more slowly, and the coefficient of variation decreases.

Another study (MVA Consultancy, 1996) included collecting and analysing data on travel time variability in the UK. It was noted that travel times for a trip vary because of variations between drivers (e.g. some drive faster than others), variations within drivers (e.g. a driver might drive faster on some occasions than others) and variations in the start time for the trip. These sources of variation can to some extent be anticipated and allowance made for them, but for a specific trip at a specific time by a specific driver, there is variability that cannot be predicted and the study focused on this source of travel time uncertainty.

The MVA Consultancy study treated trips through a network as travel through a series of 'link-junctions', where a 'link-junction' is a one-way link (the section of road between the exit from the entry junction and the entry to the exit junction) plus the exit junction. Junctions might be considered appropriate locations for boundaries between the parts of a trip, because it is at junctions that flows along a path are intersected by crossing flows and traffic flow characteristics on the path might consequently change. Whether junctions are appropriate boundaries might depend upon the form of traffic control, and, if junctions are signalised, the level of coordination of the traffic.

It was noted (MVA Consultancy, 1996) that both positive and negative correlations of the travel times on pairs of trip parts (or link-junctions) are possible. Positive correlation can occur when the travel times on pairs of trip parts are subject to common influences (e.g. bad weather, high traffic flows) or when the flow state on one part directly influences the flow state on the other (e.g. queueing in the downstream part extends back to the upstream part). The first effect might be strong when the parts are not close to each other, while the second effect is likely to reduce as the distance between the parts increases, or the lengths of the parts increase. Positive correlation means that the variance of the trip time exceeds the sum of the variances of the travel times for the parts of the trip.

It was also noted that negative correlation can occur when there is a bottle-neck in one part that restricts the flow in the downstream part and results in increased speeds on the downstream part, or the downstream part becomes congested when the upstream part is flowing freely and quickly. Negative correlation means that the variance of the trip time is less than the sum of the variances of the travel times for the parts of the trip. It is possible for a mixture of both forms of correlation to exist at the same time within a network, with the effects cancelling to some extent.

The MVA Consultancy (1996) study involved analysing two sets of data, one for links in a congested urban network and one for three reasonably homogeneous groups of links, namely motorway, inter-urban and urban links. It was found that for the first dataset, correlation generally varied between 0.2 and 0.4, and was generally greatest for pairs of 'link-junctions' that were close together. For the second dataset, it was found that the correlations between the travel times on adjacent 'link-junctions' were generally positive and often as high as 0.4, with the correlations between non-adjacent 'link-junctions' being erratic, with more positive correlations than negative correlations. The variances of the journey times were nearly always greater than the sums of the variances of the travel times for the 'link-junctions', consistent with a generally positive correlation.

Case Study of Travel Time Variability Correlation

Case Study Method

A case study of travel times on the north-bound carriageway of the Horikiri-to-Kasai section of the Central Circular Route, which is part of the Tokyo Metropolitan Expressway system, was undertaken to identify the nature and extent of correlation between the travel times for parts of trips along the section of expressway. The section of expressway is 11.9 km long and has two lanes in each direction. The geometric standard of the expressway is good, with all curve radii exceeding 1600 m and the gradients being less than 3%, except for a short section near the Kasai junction, where there is a 320 m radius curve and a gradient of about 4.1%.

The study (Munakata, 2007; Nicholson and Munakata, 2009) 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, located at spacings of 300 ± 50 metres. The daily flow rate varied a little between sections, but was generally in the range 25−27 thousand vehicles/day/lane, with about 66% occurring in the period 7am−7pm, about 7% occurring in the highest-flow hour (9am−10am), and about 65% and 35% of the traffic being cars and trucks, respectively.

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 one-minute intervals for 24-hour periods (midnight to midnight) on each of the 93 days, 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. It should be noted that the link travel times (at one minute intervals) are averages, based on about 48 and 26 vehicles during the periods 7am–7pm and 7pm–7am, respectively.

The correlation between the segment travel times was calculated for all pairs of links, for four aggregations of days: all days, weekdays, Sundays and National Holidays, and Wednesdays. The correlation coefficients were therefore compared with critical values from Fisher and Yates (1963). Analyses were also undertaken for various aggregations of links, to assess the sensitivity of the results to changes in the length of 'analysis units'.

With 39 links and data having been collected for one minute intervals, there are 741 (i.e. $[39^2-39]/2$) pairs of link correlation coefficients for each minute interval, and hence 1,067,040 (i.e. 741×1440) link correlation coefficients that could have been estimated. It was decided to consider in detail the correlation between link travel times for trips commencing during the periods 6.00am–6.01am and 1.00pm–1.01pm.

Case Study Results

The average, maximum and minimum correlation coefficients, along with the sample sizes and the corresponding critical values of the correlation coefficient, are shown in Tables 2 and 3, for the peak and off-peak periods.

It can be seen that there is considerable variation in the correlation coefficients, which range from about -0.7 to a little less than +1, with most being statistically significantly different from zero. This is not a case of 'multiple comparisons' testing finding spurious significance. Note that the averages of the correlation coefficients are generally much higher than critical values. 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 there are a few statistically significant negative correlations, suggesting the existence of a few 'bottlenecks' on the length of expressway studied.

Table 2 – Summary of Link Travel Time Correlation Coefficients (6.00am-6.01am)

	All Days	Weekdays	Sundays & National Holidays	Wednesdays
Sample Size	93	60	20	12
Critical Coefficient	±0.205	±0.250	±0.444	±0.576
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 3 – Summary of Link Travel Time Correlation Coefficients (1.00pm–1.01pm)

	All Days	Weekdays	Sundays & National Holidays	Wednesdays
Sample Size	93	60	20	12
Critical Coefficient	±0.205	±0.250	±0.444	±0.576
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

Tables 4 and 5 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 6.00am−6.01am and 1.00pm−1.01pm intervals.

Table 4 ─ Summary of Link Travel Time Variance Components (6.00am-6.01am)

	All Days	Weekdays	Sundays & National Holidays	Wednesdays
Variance term	0.32 (7%)	0.35 (9%)	0.03 (5%)	0.09 (12%)
Covariance term	4.25 (93%)	3.60 (91%)	0.60 (95%)	0.67 (88%)
Total	4.57	3.95	0.63	0.76

Table 5 ─ Summary of Link Travel Time Variance Components (1.00pm-1.01pm)

	All Days	Weekdays	Sundays & National Holidays	Wednesdays
Variance term	3.43 (9%)	4.64 (11%)	0.47 (9%)	11.01 (13%)
Covariance term	33.67 (91%)	37.60 (89%)	4.60 (91%)	74.69 (87%)
Total	37.10	42.24	5.07	85.70

It can be seen (Tables 4 and 5) 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 covariance term), which is omitted when it is assumed that link travel times are independent, is generally about ten times greater than the variance term.

A Simulation Study

As noted above, the case study results showed that the correlation between the travel times on pairs of links tended to decline as the distance between the links increased. This is illustrated in Figures 2 and 3, for the first and third of the 39 links

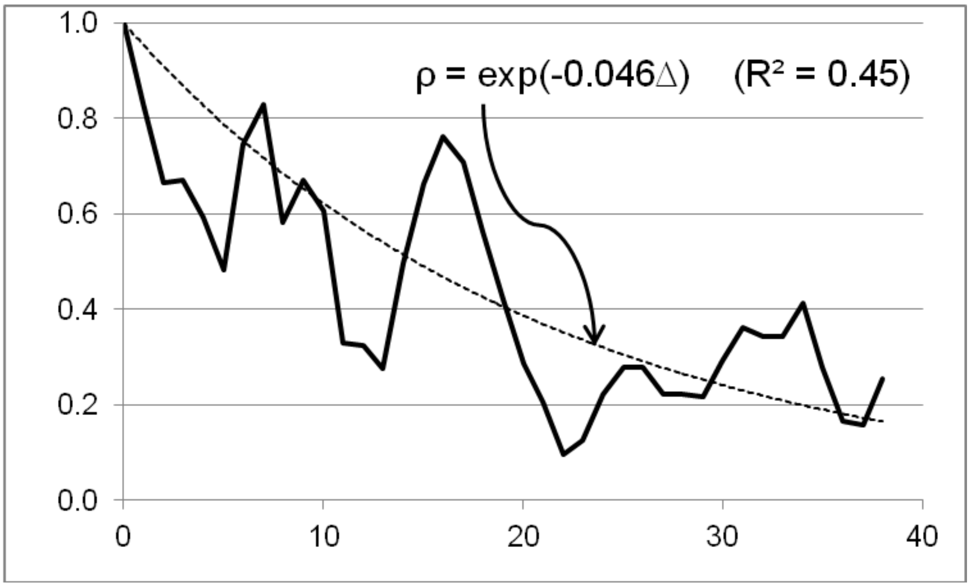

Figure 2 – Plot of Correlation Coefficient (ρ) versus Separation (Δ) for First Segment

Despite being close together, these two links show different rates of decrease in correlation with increasing separation, which is the number of links between the pair of links for which the correlation was estimated. It can be seen that the decline in the level of correlation is not smooth. Figures 2 and 3 show the best-fit exponential relationships between the correlation (ρ) and the separation (Δ). This relationship was chosen because the correlation must be unity for zero separation, and should tend towards zero as the separation increases.

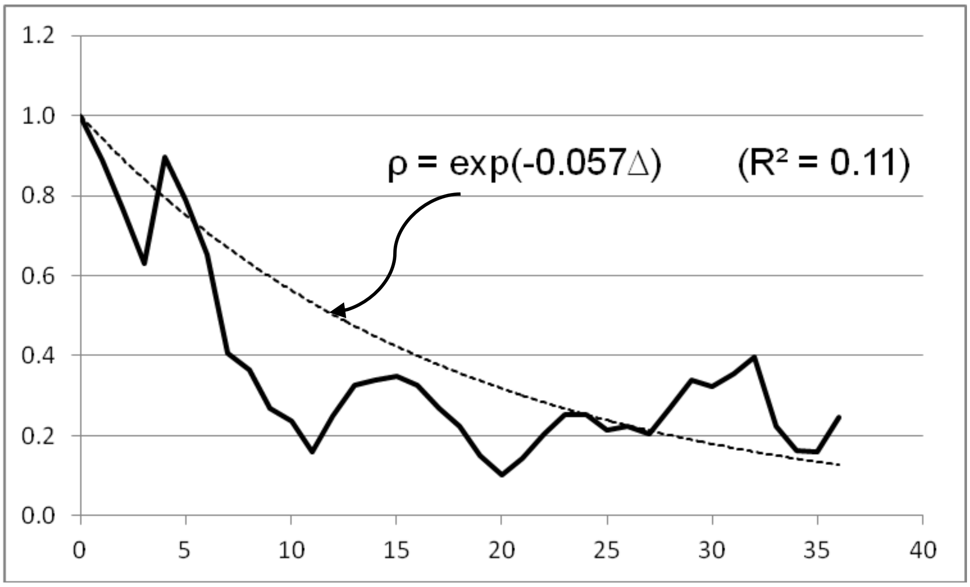

Figure 3 – Plot of Correlation Coefficient (ρ) versus Separation (Δ) for Third Segment

As noted above, several previous studies have found that travel times tend to follow a skewed distribution, with Richardson and Taylor (1978) suggesting travel times are distributed according to the Lognormal distribution. It was decided to investigate, using Monte Carlo simulation, how correlations between link travel times, along with varying levels of skewness in link travel times, influence the distribution of travel for a route comprising 40 links, where those links are of equal length (300 metres) and have the same travel time distributions.

It was decided to use the Beta distribution to describe the variation in link travel times. The advantage of this distribution over the Lognormal is that it is bounded at both the lower and upper ends of the distribution, and those lower and upper bounds are finite and positive. It was decided to set the lower and upper bound travel times at 10 s and 60 s (corresponding to maximum and minimum speeds of 30 m/s and 5 m/s) respectively.

Five combinations of the shape parameters, α_1 and α_2 were used. These and the corresponding values of the mean, standard deviation, skew and kurtosis of the link travel time distribution are shown in Table 6.

Table 6 – Input Link Travel Time Characteristics

Combination	α_1	α_2	Mean	St.Dev.	Skew	Kurtosis
I	1	1	35.00	14.43	0.00	1.80
II	2	2	35.00	11.18	0.00	2.14
III	3	3	35.00	9.45	0.00	2.33
IV	1	3	22.50	9.68	0.86	3.10
V	1	5	18.33	7.04	1.18	4.20

The trip travel time characteristics, based on 10,000 simulations for each combination of input link characteristics, were calculated for three cases:

- ignoring correlations;
- using unsmoothed actual correlations;
- using smoothed actual correlations, with $\rho = \exp(-0.05\ \Delta)$.

The results are shown in Tables 7–9 respectively.

Table 7 – Trip Travel Time Characteristics (Ignoring Correlations)

Combination	Mean	St.Dev.	Skew	Kurtosis	Coefficient of Variation	Variance Ratio
I	1400.00	91.60	0.03	2.99	0.07	1.01
II	1400.00	70.69	-0.05	2.91	0.05	1.00
III	1400.00	59.11	0.02	3.01	0.04	0.98
IV	900.00	61.10	0.11	2.95	0.07	1.00
V	733.33	44.49	0.18	3.01	0.06	1.00

Table 8 – Trip Travel Time Characteristics (Unsmoothed Actual Correlations)

Combination	Mean	St.Dev.	Skew	Kurtosis	Coefficient of Variation	Variance Ratio
I	1400.00	431.34	0.01	2.18	0.31	22.34
II	1400.00	334.30	-0.01	2.41	0.24	22.35
III	1400.00	284.39	0.00	2.55	0.20	22.64
IV	900.00	286.38	0.69	3.09	0.32	21.88
V	733.33	208.34	0.97	3.96	0.28	21.89

Table 9 – Trip Travel Time Characteristics (Smoothed Actual Correlations)

Combination	Mean	St.Dev.	Skew	Kurtosis	Coefficient of Variation	Variance Ratio
I	1400.00	421.41	-0.01	2.19	0.31	21.32
II	1400.00	329.22	0.00	2.44	0.24	21.68
III	1400.00	278.61	-0.01	2.58	0.20	21.73
IV	900.00	283.13	0.72	3.16	0.32	21.39
V	733.33	204.33	0.95	3.80	0.29	21.06

It can be seen that for all three cases, the estimated mean trip times equal the product of the mean link trip times and the number of links (as expected). It can also be seen that:

- the standard deviations of trip times are about six times the standard deviation of link times if ignoring correlations, but about 30 times the standard deviation of link times, if allowing for correlations;
- the coefficient of variation of trip times if allowing for correlations is about four times the coefficient of variation of trip times if ignoring correlations;
- for the combinations where the distribution of link travel times are zero (i.e. where $\alpha_1 = \alpha_2$), the skewness of the distribution of trip times is close to zero;
- for the combinations where the distribution of link travel times are not zero (i.e. where $\alpha_1 \neq \alpha_2$), the skewness of the distribution of trip times is;
  - much less than the skewness of link travel times, if ignoring correlation;
  - a little less than the skewness of link travel times, if allowing for correlation.

Tables 7–9 also show the 'variance ratio', which is the ratio of the variance of trip times to the sum of the variances of link travel times. This ratio is close to unity if ignoring correlations, as expected on the basis of statistical theory, but is over 20 if allowing for correlations.

The results for the two cases involving allowing for correlations are quite similar, indicating that does not appear to matter whether smoothed or unsmoothed correlations are used.

DISCUSSION

Implications for Estimation of Project Benefits

The results of the case study and the simulation study show that in some circumstances the covariance term is much larger than the variance term. This suggests that in such circumstances, the benefits of those projects, which are aimed at reducing the travel time variation for individual links, will result in a relatively small reduction in the variability of the total travel time, and that projects should be aimed primarily at reducing the covariance (or correlation-related) component of the total variance. The results suggest that in such circumstances, projects which have a small effect on the correlation-related component might well have a greater effect on the total variance than projects which have a large effect on the variance of travel times on individual links. That is, 'route treatments' might be a more productive approach to improving trip time reliability than 'site treatments'.

Another issue associated with estimating the travel time reliability benefits of projects is that current traffic assignment methods do not take account of travel time variability when predicting the flows on alternative paths through networks. This means inconsistency between the flow estimation and economic appraisal stages, and casts further doubt upon the robustness of estimates of the travel time reliability benefits of road network improvement projects.

A series of studies were undertaken by Mott MacDonald (2000a, 2000b and 2003), allowing for correlations within the range 0.2 to 0.4, as found by the MVA Consultancy study, between adjacent links only. Those studies were aimed at developing a practical method for including travel time variability in the assignment of traffic to a road network. Without such an assignment method, an economic appraisal of a road network improvement project designed to reduce travel time variability might not produce an accurate result, as the link and junction flows used in the economic appraisal might well be very different to those that would occur if drivers took account of travel time reliability when deciding their route through the network.

As noted above, the standard deviation of travel time for a trip is not simply the sum of the standard deviations of the travel times for the parts of the trip, and Mott MacDonald (2000b) state that this non-additivity is "a key problem" for assignment algorithms. The seriousness of the problem is illustrated by the comment in Mott MacDonald (2003) that including the standard deviation of travel times in the generalised cost function means that the fundamental assumption of minimum cost path finding algorithms (that each part of a minimum cost path is itself a minimum cost path between the end points of that part) is violated.

Mott MacDonald (2000b) state that "the presence of correlations between link travel times is a further complication but can be seen as essentially just another cause of link non-additivity".

Mott MacDonald (2003) commented that using the variance of travel time rather than the standard deviation, to preserve the additivity of the generalised cost function, would solve the problem "only if correlations between link travel times are also neglected". Mott MacDonald (2000b) did note that while their study had not included correlations between non-adjacent links, "additional research in the future might be needed to examine the effect of ignoring correlations between non-adjacent links". The case study has shown that ignoring correlations between the travel times of adjacent and non-adjacent links is not appropriate in all circumstances.

Scientific Significance and Statistical Significance

Allowing for correlations between travel times on adjacent and non-adjacent segments of trips does complicate both traffic assignment and economic appraisal, and one might therefore be tempted to omit consideration of the effects of such correlations if the correlations are weak and not statistically significantly different from zero.

The case study has revealed correlations which have mostly been strong and statistically significant, and clearly should not be ignored, as statistical theory shows that estimates of trip time variability are likely to be biased if one ignores statistically significant correlations.

Even if the correlations had been weak and not statistically significant, ignoring them (i.e. treating them as if they are zero) would be inappropriate, because the covariance term comprises a large number of elements, and the covariance term can consequently be substantial. As found by Giacomini and Granger (2004), who were investigating the relative efficiency of different methods of forecasting the aggregate of spatially correlated socio-economic variables, ignoring correlation, even when it is weak, can result in highly inaccurate forecasts. As noted by Armstrong (2007), it is important to distinguish between statistical significance and scientific significance. The scientific significance of correlation coefficients depends upon how they are to be used. Even if correlation coefficients are weak (i.e. not statistically significantly different from zero), they can be scientifically significant.

CONCLUSION

While the standard deviation is commonly used as a measure of travel time variability, it should be noted that it does not give any indication of the level of skewness in the distribution of travel times. There is considerable evidence that travel times are positively skewed, with a long upper tail, reflecting infrequent travel times much larger than the expected value, and a short lower tail, reflecting frequent travel times a little less than the expected value. There appears to be a need for consideration of the skewness of travel time distributions when estimating the benefits of projects to reduce travel time variability.

This case study, using data for part of the Tokyo Metropolitan Expressway system, has revealed strong evidence of correlation of travel times for the sections of the expressway. While these results differ from those obtained in some earlier studies, other previous studies have revealed evidence of correlations between adjacent (or adjoining) links. The results of the Tokyo Metropolitan Expressway case study indicate that correlations between non-adjacent links can also be substantial. Further research, to identify clearly the circumstances in which it is important to allow for correlations, and which correlations to allow for, is needed. Further research is required to identify a practical and scientifically sound method for incorporating travel time variability within route choice modelling, so that an economic appraisal, which includes estimates of the economic benefits of reductions in travel time variability, uses estimates of flows which reflect the route choice behaviour of travellers whose route choice is affected by travel time variability. Otherwise, estimates of the economic benefits of reductions in travel time variability are likely to be inaccurate.

The research results show that there is a need to include consideration of the effect of correlation of travel times on different parts of trips, when estimating the benefits of projects to improve trip time reliability. Otherwise, the benefits of projects, designed to reduce the variability of travel times for particular parts of networks, are likely to be over-estimated considerably. This is likely to hold even when the correlations are not as high as found in this research and are not individually statistically significant, because the large number of correlation-related terms contributing to the total travel time variance means that they are collectively ‘scientifically significant’.

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’.

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