# FORECASTING AND APPRAISING TRAVEL TIME VARIABILITY IN URBAN AREAS: A LINK-BASED APPROACH

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## 1 Introduction

A previous paper (Black I et al, 2008) demonstrated how data collected from Global Positioning System (GPS) tracker equipped vehicles could be used to develop a relationship between travel time variability (TTV) and the level of congestion. Data from 34 routes in 10 urban areas were analysed and the final recommended equation for a route of length d (km) in an urban area was

$$CV_t = 0.16 CI_t^{1.02} d^{-0.39}$$

where:

$CV_t$ is the Coefficient of Variation (standard deviation of travel time divided by average travel time) in a time period t (e.g. 09:00-09:30); and

$CI_t$ is a Congestion Index (average travel time divided by free flow travel time) in the same time period t.

This equation was found to be fairly robust in explaining TTV on the sample of 34 routes. The use of distance and average travel time means that the equation can use standard outputs of transport modelling packages. One potentially unsatisfactory feature is the absence of any reference to the features of the links that make up a journey (such as length and type of junction). This paper describes work carried out for the Department for Transport (DfT) (Hyder Consulting, 2009) to examine whether an alternative model that takes account of link features is preferable. This is referred to as a link based model as opposed to the distance based model described in the previous paragraph. The analysis uses the same data as that used for the distance based model i.e. 34 urban routes comprising 541 links. Data was collected on the link characteristics and parameters of a link based model were estimated. Finally the goodness-of-fit for the two models was compared.

## 2 Data

Journey time data is derived from a database ITIS/CJAMS (Congestion and Journey-time Acquisition and Monitoring System) which collates and processes GPS data provided by individual probe vehicles. The data collected includes information on the location of vehicles equipped with GPS. The location is reported at regular time intervals while their ignition is switched on.

The analysis conducted in this research is based on data from the 10 largest urban areas in England, from which a minimum of three major road routes within each area were selected. There are a total of 34 routes, of which some are short (less than 5 km) and a few have an average link length greater than 700 metres. These routes are representative of major urban roads but with a higher standard and higher average speed limit than average urban roads. For this research, only records from Cars and LGVs are used.

From the Journey Time dataset standard deviation of travel time is calculated for 15 or 30 minute intervals during the period 0700-2200. The standard deviation of travel time is calculated for each link on a route and also for combinations of successive links.

The second set of data collected is concerned with link characteristics for the 34 routes. Links are generally defined as sections of route between junctions which will cause some delay to traffic using the route. The variables for which data was collected (Table 2.1) are split into those related to the junction at the downstream end of the link and those that reflect conditions along the link that may influence vehicle flow (friction variables).

At very low flow levels the standard deviation of delay (and also travel time) is determined by the type of junction at the downstream end of a link and in the case of traffic lights the signal settings. In the case of priority junctions (such as roundabouts) delay will be minimal and the standard deviation of travel time near zero. In the case of traffic lights arrival in the red cycle leads to delay due to the need to wait for a green signal and queuing vehicles to be released. The longest wait during the red signal is the duration of that signal, the shortest is zero. With very low flow, random vehicle arrivals, and no delay caused by the need for deceleration and acceleration, the expected (or average) delay, $D_0$ is

$$D_0 = \left(\frac{R}{G+R}\right)\left(\frac{R}{2}\right)$$

where R and G refer to red and green times respectively.

The general term for travel time standard deviation at very low flow is

$$SD_0 = \left(\frac{R^3}{3(R+G)} - \left\{\frac{R^2}{2(R+G)}\right\}^2\right)^{0.5}$$

In the list of variables within Table 2.1, SDOP represents this minimum level of standard deviation in delay (travel time).

**Table 2.1: Link Characteristics**

| Characteristic | Unit | Code |
|---|---|---|
| **Junction Variables** | | |
| Link length | Metres | LINL |
| Speed limit | Miles per hour | SPDL |
| Signal junction | 0,1 | JSIG |
| Theoretical SD at low flow | Seconds | SDOP |
| Signal – total cycle time | Seconds | SIGC |
| Signal – green time | Seconds | SIGG |
| Number of arms of the junction | Number | NRMO |
| Number of lanes in the arm | Number | NRMI |
| **Friction Variables** | | |
| Link length | Metres | LINL |
| Speed limit | Miles per hour | SPDL |
| Lanes along the route | Number | NLAN |
| Side roads on the left | Number | NRDL |
| Side roads on the right | Number | NRDR |
| Frontage development to left | Percent | DEVL |
| Frontage development to right | Percent | DEVR |
| Width of carriageway | Metres | CARW |
| Lanes to the left of the movement | Number | LNSL |
| Lanes to the right of the movement | Number | LNSR |
| Bendiness 1 Crow fly distance | Metres | BND1 |
| Bendiness 2 Actual distance | Metres | BND2 |
| Parking permitted on the left | Percentage of link length | PARK |
| Pedestrian crossings | Number | PEDC |
| Delay due to pedestrian crossings | Seconds | DPED |
| Online bus stops | Number | ONBS |
| Offline bus stops | Number | OFFB |
| Presence of bus lanes | 0,1 | LANB |
| Presence of cycle lanes | 0,1 | LANC |
| Zebra crossings | Number | ZEBC |

## 3 Single Link Analysis

A relationship between the standard deviation of travel time (SD) and delay can be established for each link with a linear regression model. Delay is defined as the difference between the average observed travel time for a set of travellers (observed travel time) and minimum or reference travel time found on the link. The form of model for a single link is as follows:

$$SD_t = \alpha + \beta D_t$$

where: $SD_t$ is the standard deviation of travel time in time period t (secs)
$D_t$ is the delay for the link in time period t (secs)
$\alpha$ is the intercept;
$\beta$ is the slope; and
t is the time period (0700-0730,…..2100-2130).

The goodness of fit and sample size are recorded for each link regression.

Reference Time is defined as the mean time to traverse a link in very low flow conditions. It is also referred to as free-flow time. It is a mean figure because with signalised junctions the time for an individual vehicle will vary depending on arrival time at the signals. The reference time for each link is calculated from the observations during the hours between 00:00 and 06:00.

Some links are excluded because of low sample sizes or the link characteristics changed during the period of data collection. A total of 458 links remained after this filtering process had been applied. One cautionary note should be made concerning the data. A travel time estimate for a link is not based on observations at the beginning and end of the link but instead by interpolation from two GPS observations that will very rarely coincide exactly with the beginning and end. This does introduce some bias into the figures for average travel time and estimates of standard deviation of travel time. A precise measure of this bias is not available. However it is possible to conclude that the bias is likely to be most severe for short links.

The analysis identifies the intercept and slope parameters of the relationship above and then uses regression analysis to test for the significance of the different link characteristic parameters found for individual links. Parameter estimates are made for the whole sample and also by link length category (<400m, 400m-800m, >800m) and maximum delay (<40 seconds, 40+ seconds).

The findings concerning the first parameter, the intercept (Figure 3.1), show that the empirical data on SD at low traffic flow is broadly consistent with theory as represented by SDOP. Link exits in the case of roundabouts exhibit intercepts near zero, whereas those exits with traffic signals show a minimum SD consistent with the traffic light settings.

**Figure 3.1 Estimated Intercept Parameter**

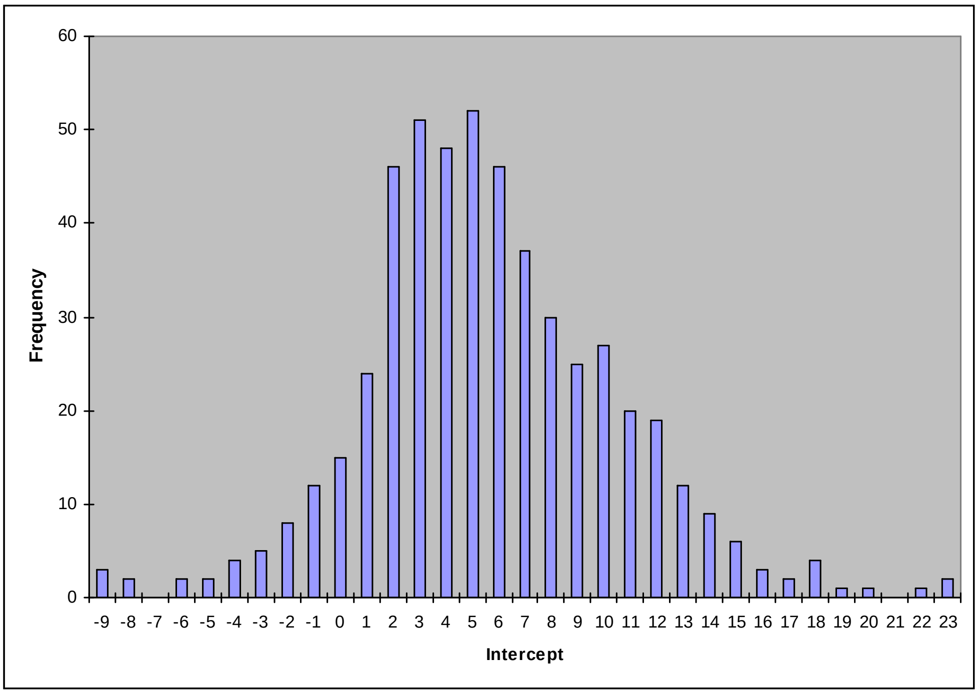
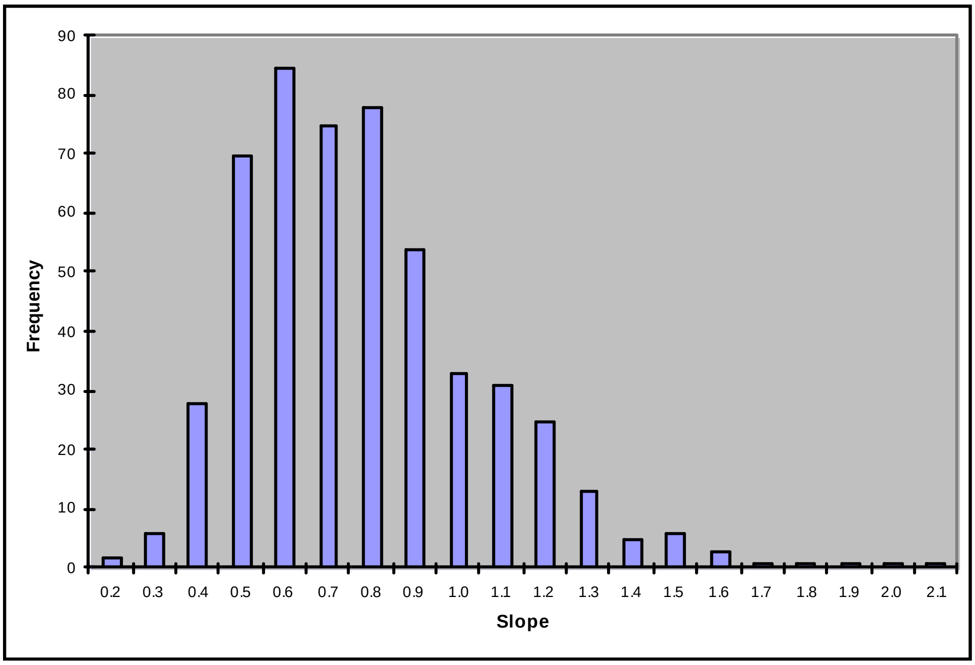


**Figure 3.2 Estimated Slope Parameter**



In the case of the second parameter concerned with the slope of the SD-Delay relationship (Figure 3.2) the findings are far from transparent. Two parameters PEDC and SPDL do demonstrate significance in some samples. There is some theoretical reasoning to justify PEDC as a variable affecting the slope as under certain circumstances (dependent on the method of control and frequency of use) pedestrian crossings will have an effect similar to a traffic light controlled junction. In the case of SPDL this seems to be reflecting the difference in link characteristics on roads with 30mph and 40mph speed limits, rather than the speed limit per se. Even when these variables are taken into account (and the evidence is not particularly robust) only a small proportion of the variation in slope is explained (about 10%). This lack of any important explanatory variables concerning link characteristics lends support to the proposition that for the type of links found in this sample (a range of urban major road link standards) a simple model in which delay is only caused by junctions is sufficient i.e.

SD = maximum {SDOP, (0.7*Average Delay)}

The minimum value is defined by the SDOP formula based on green and red cycle times at junctions. The coefficient is based on a compromise. For the universal data set the slope is estimated at 0.62. The average slope found from individual link estimates is 0.73.

This conclusion is unsatisfactory in the sense that there is clearly a significant difference in slope parameters between links. If the explanation does not appear to be due to link characteristics then there must be some other explanation. The two remaining candidates to explain the variation are day to day variability in demand (DDVD) and capacity (DDVC). Monte Carlo simulation demonstrates that there is a near proportional relationship between DDVD and the parameter $\beta$. It seems incontrovertible that DDVD and to a lesser extent DDVC play some role in explaining the variation in slope that is found in the sample. The lack of evidence for a major influence of link and junction characteristics on the slope parameter suggests that the DDVD/DDVC role is the major one.  Data on DDVD and DDVC is not currently available. In future research collection of this data should be a priority.

## 4 Multi Link Analysis

The previous sections examined the impact of congestion (delay) on travel time variability (standard deviation) on an individual link basis. Analysis of single link data provides an empirically derived equation of the form

$$sd_t = f(delay_t, SDOP)$$

However this equation has only limited use unless it can be applied for journeys comprising several links.

For a journey comprising N links Average Travel Time, Reference Time and hence Average Delay (Dlay) is the sum of the average delays on individual links:

$$Dlay_n = \sum_{n=1}^{n=N} Dlay_n$$

The estimation of route Standard Deviation is more complex. The standard deviation of travel time for a journey involving several links can be found only if assumptions are made about the correlation of delay between links.

Two models are examined. The first assumes only adjacent link correlation (ALC) i.e.

$$\sigma^2_{1+2+3+...N} = \sigma^2_1 + \sigma^2_2 + \sigma^2_3 ......+ \sigma^2_N + 2r_{12}\sigma_1\sigma_2 + 2r_{23}\sigma_2\sigma_3.....2r_{N-1N}\sigma_{N-1}\sigma_N$$

where $\sigma_n$ is the standard deviation of journey time on link n.

This shows that the delay variance of a journey is the sum of variances for individual links (1, 2, 3,….N) providing there is no correlation between links. The second half of the formula shows the impact of correlation between adjacent links (12, 23, 34,…..(N-1)N). It does not include the impact of correlation between non-adjacent links (13, 24, 35,……..etc).

An alternative is to assume an autocorrelation (ALAC) model. Most autocorrelation models deal with correlation in errors in time series. Our interest is in deviations from minimum travel time on a link.

If it is assumed that

$$d_{l+1} = rd_l + \varepsilon_t$$

where: $d_l$ is the delay on link l
$\varepsilon_t$ is a stochastic variable

Using this assumption leads to a correlation of r between adjacent link delay. It also leads to a correlation of $r^2$ between link l and link l+2, and $r^3$ between link l and l+3. For a four link model the relevant equation is

$$\sigma^2_{1234} = \sigma^2_1 + \sigma^2_2 + \sigma^2_3 + \sigma^2_4 + 2r(\sigma_1\sigma_2 + \sigma_2\sigma_3 + \sigma_3\sigma_4 + r(\sigma_1\sigma_3 + \sigma_2\sigma_4) + r^2(\sigma_1\sigma_4))$$

In order to find the correlation coefficient implicit in empirical data there are two methods available:

1. Using single link data for a route estimate the correlation coefficient (ALC or ALAC) that is required to match the multilink data for that route. The estimates of ALC and ALAC are related. ALAC will always be lower than ALC.
2. Adjacent link correlation can be calculated directly from travel time observations for link l and link l+1 (only for cases recorded for the same vehicle). In the context of ITIS/CJAMS data the interpolation method used to determine link travel terms is likely to provide biased estimates for short links, with consequent bias in the correlation coefficient. The scale and direction of that bias is difficult to determine.

A total of 24 routes were used for the analysis. Figure 4.1 shows the estimate of ALC from the two methods (2link refers to method 2). The two methods show a similar distribution of the correlation coefficient though the multilink method is about 0.05 on average below that derived from method 2. The mean is 0.41 (method 2). Figure 4.2 shows the variation over the day for the average (all routes) and two individual routes. As the figure shows there is a slight tendency for the figure to be lower during the middle hours of the day, though this is not statistically significant for most routes.

**Figure 4.1: Estimates of Correlation**

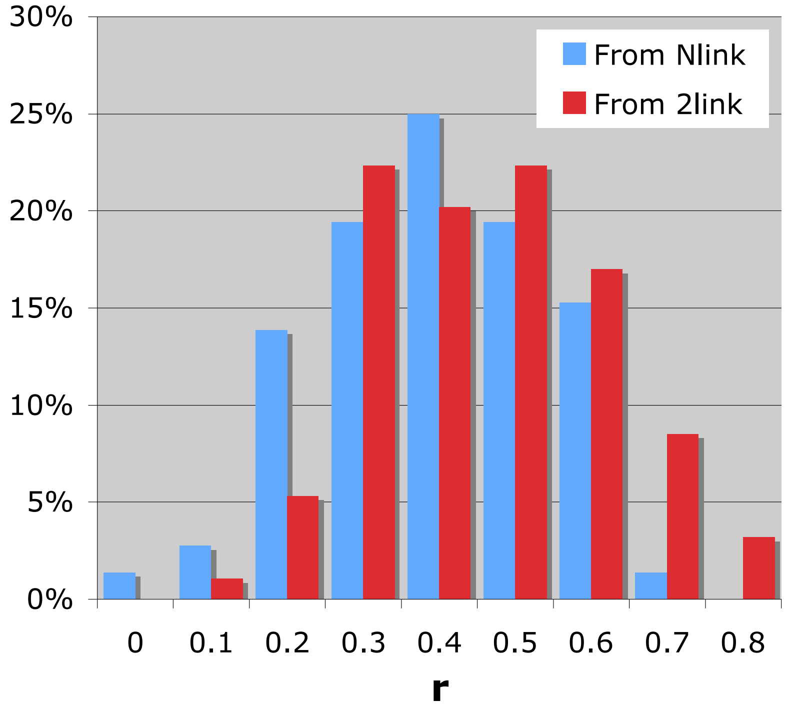
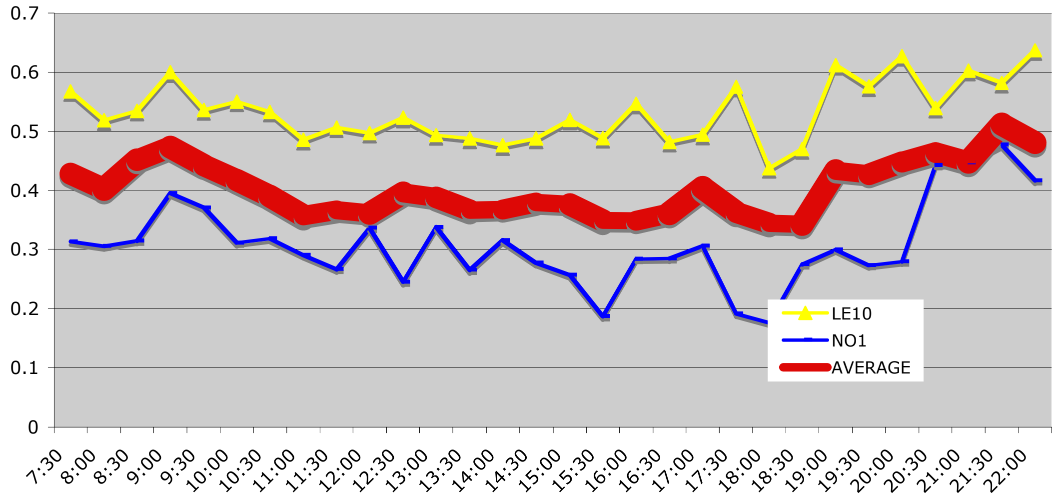


**Figure 4.2: Correlation over the Day**



Regression analysis is used to identify possible factors behind the variation in r between routes. There is strong evidence that traffic lights reduce the correlation by about 0.1. Link length of adjacent links is also statistically significant (negative slope 0.06 per 1000m). However this may not be a real underlying cause. The interpolation method used to estimate link travel times is likely to lead to some spurious correlation particularly for short link lengths.

The final question is to consider the relative merits of using ALC or ALAC. Using the individual link data it is possible to calculate the correlation between links *l* and *l+2*, and comparing it with the correlation between link *l* and *l+1*. For a sample of 27 link pairs the correlation between link *l* and *l+2* is above zero and approximately in the range implied by the autocorrelation model. This provides support for the autocorrelation model (strictly speaking it provides support for positive correlation between links *l* and *l+2*). Overall the average correlation for this sample (*l l+2*) is 0.128 implying an ALAC estimate of 0.358, which is close to the average adjacent link correlation for this sample of 0.380.

## 5 Comparison of distance and link based models

In this section the goodness of fit of the link based model described above is compared with the distance based model. The distance based method predicts the Coefficient of Variation (CV - standard deviation of travel time divided by average travel time) for a journey in a time period t as a function of a Congestion Index (CI - average travel time divided by free flow travel time) and the length (km) of the journey from the formula:.

$$CV_t = 0.16 CI_t^{1.02} d^{-0.39}$$

With a simple transformation this formula can be used to predict SD in a journey time period.

The goodness of fit is calculated using the same 40 routes and the same inputs (average travel time, reference time) that were used in the previous section. The total sample was split into seven categories by sample size (i.e. number of time periods) and SDTable 5.1 summarises the results of this analysis.

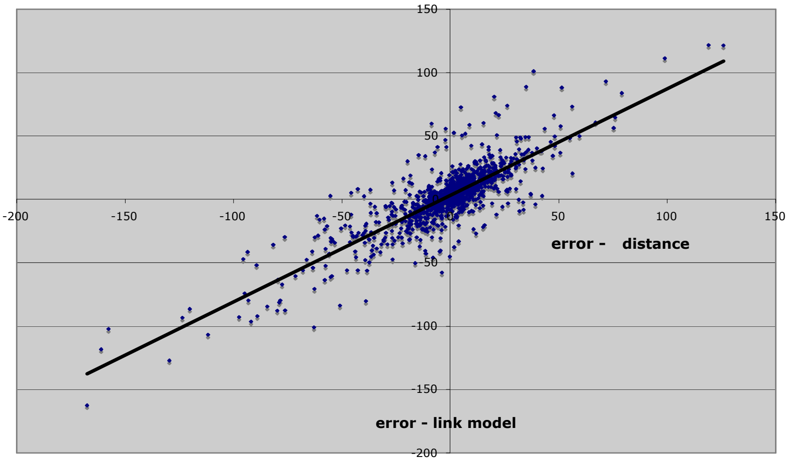
The last column of Table 5.1 shows the Standard Error from the distance-based analysis. Comparing the link based results with these standard errors suggests the difference in accuracy for the two models is minor and that they are performing similarly.

**Table 5.1: Comparison of Distance and Link Based Models**

| Category | Sample Size | Link Based Standard Error | Distance Based Standard Error |
|---|---|---|---|
| Sample size >0 | 1167 | 24.9 | 25.0 |
| Sample size >30 | 636 | 19.5 | 19.6 |
| Sample size >50 | 410 | 18.4 | 18.3 |
| Sample size >100 | 158 | 15.3 | 15.1 |
| Observed SD>50 | 703 | 30.2 | 29.6 |
| Observed SD>100 | 299 | 37.0 | 37.1 |
| Observed SD<100 | 868 | 16.3 | 16.1 |

Figure 5.1 compares the errors derived from the two models (total sample). This shows that both models are performing poorly in the same situations, which is not surprising when we consider the basis of the two models. For a given journey both models use the travel time of the individual links of the journey. This set of travel times is transformed in both models using just two parameters. One parameter in each case handles the response of SD to changes in delay (congestion). Both transformations are monotonic and will (by the process of fitting) have similar responses in SD as travel time (delay) changes. It is clear by examining the errors of the two models that minor adjustments to the model form will not explain the large errors.

**Figure 5.1 Comparison of Distance and Link Based Model Errors**



## 6 Conclusions

This paper has described a link based model that predicts travel time variability (TTV) in urban areas. It has demonstrated that a model based on a simple single link SD-Average Delay function and summing variances (with due allowance for adjacent link correlation) is as powerful in explaining TTV as a model based on a congestion index and distance. In its basic three parameter form $\alpha_l$ $\beta$ $r_l$ it performs as well as the distance based model. Greater sophistication by adopting SDOP rather than a fixed constant $\alpha_l$ and a variable $r_l$ depending on junction configuration has potential to improve the model.

A number of suggestions can be made as to how the model might be improved. In using GPS data a priority is to remove (or at least identify) bias in the estimate of link travel times, which is particularly important for short links. Closer examination of the distribution of link travel time should yield some further insight (there is a distinct tendency for a longer tail at high travel times).

Whilst these considerations may lead to some improvements in the accuracy of the model, there remains in the link based model (as in the distance based model) an inherent variation in the parameters (essentially the slope related to SD-Delay) found on individual links (and by implication journeys over a number of links). The recommended relationship should therefore be recognised as an average relationship. Behind this average significant differences between links (and journeys) can be observed, epitomised by the distribution of slope seen in Figure 3.2. Logic leads to the conclusion that this variation is caused by day to day variability in demand (DDVD), and to a lesser extent capacity (DDVC). If there is to be a step improvement in models of this form then the issues of DDVD and DDVC will need to be addressed. Although the data used in this research yielded fairly robust estimates of adjacent link correlation in travel times, there remains little in the way of theory to explain the factors behind different levels of correlation. This issue is also a priority in future research.

The final comment is that the way forward must lie with a link based model. Unlike the distance based model this can incorporate factors such as DDVD and correlation at a link level.

## Bibliography

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## Note

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