Cost-benefit analysis of road widening proposals with special reference to the M2 Motorway in the Sydney region: a statistical evaluation

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Abstract

The methods of cost-benefit analysis (CBA) endorsed by road authorities in Australia and New Zealand do not adequately address the general problem of accuracy and uncertainty. This problem has to be resolved if CBA is to be acceptable for decision making particularly in critical applications. It is not sufficient merely to carry out a sensitivity test using changes in the discount rate. All quantities in the analysis are subject to uncertainty and it is necessary to determine statistical confidence intervals for the mean values.

This paper illustrates this principle. It is an approximate cost-benefit analysis of a proposal to widen the 21 km M2 Motorway in the Sydney region from four to six lanes. Travel speeds, accident rates and vehicle operating costs are treated as three continuous random variables and sample statistics are derived from both the unwidened and widened road. The sample differences for each of the three variables are shown to be approximately normally distributed using the Kolmogorov-Smirnov goodness of fit test. This test is shown to be the appropriate one in this application. In evaluating the statistical significance of the mean sample differences, recognition has been given to the problem of unequal variances in applying the t-distribution. It is shown that this difficulty can be overcome by adjusting the number of degrees of freedom in the distribution. All mean differences are shown to be statistically significant and the related confidence intervals are evaluated.

The analysis evaluates both the net present value (NPV) of the costs and benefits and the benefit-to-cost ratio (BCR) over the remaining concession period of 36 years, measured from the expected completion of widening in 2012. The discount rate used has been determined from published financial data of the Transurban Group. The use of the weighted average cost of capital (WACC) as the discount rate is a recognition that the M2 Motorway is a business enterprise with costs attached to its operation and is essentially selling travel time savings to the road user for a toll fee. It is not a public road and the social discount rate is therefore inapplicable. In the analysis the stated cost of construction is $550m and the costs of leasehold rent and maintenance are ignored, thus favouring the project. From a socio-economic viewpoint, there is unlikely to be any significant reduction in accident costs.

It is shown that the inflation adjusted value of BCR lies within the range 0.13 to 0.42, with 95% certainty, with a mean value of 0.27. As the benefits are very much less than the costs, the project fails to satisfy the economic criterion as required under the Environmental Planning and Assessment Act and its Regulation. The project cannot therefore be properly characterised as “critical infrastructure” as defined in the Act and as claimed by the proponents.

It is to be noted that the project proponents, the NSW Roads and Traffic Authority (RTA) and the Transurban Group have endorsed a value of BCR = 3.4, without any uncertainties quoted. As this value is over 12 times the properly derived mean value it should be rejected as it suggests an influence of predetermination and bias in favour of the project. The legal implications of this gross discrepancy are discussed.
1. Introduction: the background to the M2 widening proposal and the reasons for this analysis

On 27 February 2009, the then NSW Minister for Planning, Kristina Keneally, declared that the M2 upgrade involving inter alia, the widening of sections of the eastbound and westbound carriageways, is:

“a critical infrastructure project, having formed the opinion that the project is essential for the State for economic, environmental and social reasons”.

An application by the author to the NSW Roads and Traffic Authority (RTA) to obtain under Freedom of Information (FOI) the reasons why the project was “essential for the State” was unsuccessful. In a letter to the author dated 2/3/2010, the RTA revealed that the correspondence between it and the Transurban Group, the owners and operators of the M2 was extensive and would have taken the Authority an estimated 170.5 hours to process the FOI application as it would have involved 10 different areas of the Authority. The RTA’s response indicated that the Transurban Group had been negotiating with the RTA since at least 2006, soon after it had taken over the M2 from the Hills Motorway Group.

This cost benefit analysis has been undertaken to examine whether an economic reason for widening the road really existed as claimed by the Minister for Planning. The NSW Environmental Planning and Assessment Regulation 2000 in Schedule 2 requires, inter alia, an economic justification for such a proposal. The results of this analysis based on the use of mathematical statistics and probability show that such an economic justification cannot be supported.

2. The congested state of the M2 in the eastbound direction during the AM 2 hour peak period.

The congested state of the motorway during the AM peak eastbound period could have been predicted had a proper analysis of the road network in the M2 corridor been carried out prior to the RTA’s statutory determination to proceed with the M2. The M2 consultant, Gutteridge Haskins and Davey (GHD, 1994)) assumed that the M2 would behave like another toll road, the M4 and adopted without proper justification the same factor of six relating the AM 2 hour peak traffic to the average annual daily traffic (AADT). In Appendix A the author has derived the mean factor F for the M2 based on the RTA traffic census results for 1996 applied to six feeder roads in the M2 corridor. The 95% confidence intervals and means for these factors \( F_e \) and \( F_w \), for easterly and westerly traffic flows respectively are summarised here:

\[
F_e = [3.5, 4.6, 5.6], \text{ and } F_w = [6.6, 8.0, 9.5].
\]

It is clear that the GHD factor of six lies outside the 95% confidence limits, raising serious doubts that this factor was in fact derived from counts in the M2 corridor as well as the M4 corridor as claimed by the M2 consultant.
Figure 1: A 13-year history of the lane loadings on the eastern lanes of the M2 during the AM peak period

These lane loadings were calculated from the actual AADT value in each year using (a) the fiducial range of factors derived from the local traffic network, and (b) the GHD factor of six obtained from the M4 Motorway. It will be observed that the GHD factor is consistent with the AM peak traffic reaching the lane capacity value of 2000 vehicles/lane/hour in 2009, corresponding to a level of service described as queuing and delays (Austroads, 1988). Nevertheless, GHD claimed that

“the M2 Motorway would only reach 85% of its capacity in both directions by the year 2027 in both directions”,

and that its factor was not only derived from the M4 motorway but also from

“traffic counts within the M2 corridor”.

Information about the asserted “traffic counts” in the M2 corridor was not revealed. The GHD claim is analysed in detail in Appendix A.

The evidence presented in this paper suggests that the widening proposal appears, inter alia, to be a costly attempt to compensate for the gross errors in prediction described above. As shown by the author (Goldberg, 2006) the forecasts for the M2 were financially engineered by a work back process. A similar process resulted in the financial collapse of the Cross City and Lane Cove Tunnels. In both these cases the traffic forecasts were matched to the desired outcome for equity investors, but as the predicted values were not based on proper considerations of land use and transport interaction, it is not surprising that the projects failed. In the case of the M2 the failure is an economic one in which the road user pays continually increasing tolls for a level of service which continues to deteriorate with time. The financial viability of the M2 is unclear because it was taken over by the Transurban Group in 2005. However investigation suggests that its financial viability was dependent to a substantial degree on interest income derived under the Infrastructure Borrowings scheme (Sieper, 1995). The M2

1 The cash flow statements for the Hills Motorway Group owners and operators of the M2 reveal a critical dependence on infrastructure bond interest to maintain solvency.
widening proposal creates the perception that if more road space is made available by widening at very considerable capital cost stated to be $550 million, the level of service will improve. Such an idea ignores the influence of traffic induced by the availability of more road space (Litman, 2009; Mackie, 1996, SACTRA, 1994). The fundamental importance of traffic induction has been summarised by Litman (2009) quoting from SACTRA and Mackie:

".. the economic value of a scheme can be overestimated by the omission of even a small amount of induced traffic. We consider this matter of profound importance to the value-for-money assessment of the road programme. (SACTRA,1994)".

and

"..quite small absolute changes to traffic volumes have a significant impact on the benefit measures. Of course, the proportional effect on scheme Net Present Value will be greater still". (Mackie, 1996).

It would have been very difficult to include the influence of induced traffic into this cost benefit analysis, but it is sufficient to state that traffic induction will occur as has already been demonstrated particularly by the behaviour of the east flowing traffic in the AM peak period which has continued to increase over the last 13 years. The widening proposal incorporates additional ramps which can only exacerbate the problem of induced traffic. A best case outcome for the project is analysed in this paper. It is assumed that no widening of the four lane road has occurred, where in actual fact 6.5 km of the western lanes have been modified from two to three lanes. This represented less than 8% of the total lane length. The calculated changes will therefore tend to overestimate to a small degree what will occur in practice.

3. Cost benefit analysis of the M2 widening proposal

The following variables are involved in the cost benefit analysis (CBA):

(1) The savings ($T$) in travel time brought about by increased traffic speeds due to the reduced traffic densities on the widened road compared to that on the original road;

(2) The reduction in accident costs ($A$) as a result of reduced traffic densities on the widened road compared to the original road;

(3) the reduction in vehicle operating costs ($VOC$) as a result of speed changes on the widened road compared to the original road; this “reduction” will in fact be shown to be an increase in costs due to the higher speeds allowed by the widening.

(4) The capital cost $C_0$ of the reconstruction,

(5) The discount rate ($r\%$ pa) which is used to calculate present values and net present values. It is assumed to be constant with time for the purpose of this analysis.

Overall, the above five items will be those quantified, in principle, the cost of maintenance and freehold rent should also be included. However models for these quantities are not available and other variables such as the cost of noise are difficult to quantify. It is sufficient to note that the inclusion of these last two quantities would reduce even further the net present value (NPV) of the project.
3.1 Cost benefit analysis and the discount rate

It is appropriate to consider first the discount rate because the future costs and benefits determined by calculation of the above quantities have to be aggregated and reduced to a single value. This reduction is carried out by discounting the values referred to above and the rate at which discounting occurs is known as the discount rate. The discount rate is simply an interest rate.

As a simple example of the meaning of the discount rate concept, consider the end result of investing $100 at an interest rate of 5.7% pa for a period of 10 years. The value at end of the investment term is $(1.057)^{10} = $174 but the value now is not $174 but is only $100. We can say that the present value of $174 received in the future is $100 when the discount rate is 5.7% pa.

3.2 The two principal discount rates used in cost benefit analysis

In cost benefit analysis there are a number of discount rates that can be applied to projects (Sassone and Schaffer, 1978), but for this analysis it is necessary and sufficient to consider two only. These are the social discount rate (SDR) and the market discount rate (MDR). These two rates reflect two different concepts. The use of social discount rate implies that society can wait a much longer period for a return on investment than is the case for business enterprises where the market rate is appropriate. Society continues indefinitely whereas business has a relatively shorter time span.

3.3 The discount rate applicable to a toll road

The market discount rate is the one used in this analysis for two fundamental reasons. First, the M2 Motorway is a private toll road; essentially it is a business operation with a limited concession life and its usage is not free to society. Second, its financial performance depends on the traffic supplied to it by the public road system. Moreover it pays no rent for this advantage. The author (Goldberg, 2009) has calculated a discount rate $r = 13.7\%pa$ based on a discounted cash flow method. This rate is essentially the weighted average cost of capital (WACC) and includes consideration of an appropriate risk premium derived from market data.

For a given discount rate $r \%pa$ the sum of the discounted cash flows is required. If at the outset we have calculated a benefit amount $B$ for a particular quantity, whether it is travel time savings (T), savings in accident costs (A) or savings in vehicle operating costs (VOC), then in subsequent years the present value (PV) of the same amounts at the discount rate $r\%pa$ will be:

$$PV = B + B/ (1+r) + B/ (1 + r)^2 + B/ (1+r)^3 + \ldots \ldots \ldots$$

Using the formula for the sum of a geometric progression with common factor $1/ (1+r)$, we have

$$PV = B. \left[ 1/ (1+r)^n - 1 \right] / \left[ 1/ (1+r) - 1 \right]. \quad (1)$$

If $n = 36$, $r = 13.7\%pa$, $PV = 8.3$, for the market discount rate over 36 concession years. An increase of approximately 1\%pa in the discount rate would reduce PV to 7.9, a reduction of approximately 5%. But the overall uncertainty of the CBA is shown below to be 29% so that a dependence on discount rate alone would lead to erroneous conclusions about the overall uncertainty of the evaluation.

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2 The rate of 5.7\%pa is the current Commonwealth 10 year bond rate as at 7 April, 2010.
3 The author showed that the 95% confidence interval for WACC was $[12.8, 13.7, 14.6]\%pa$.
4 The dependence on discount rate only is endorsed by Austroads (1996) in Benefit Cost Analysis Manual.
This value of PV = 8.3 will be used as the multiplier for the initial costs and benefits in year 1 (2012), to obtain the sum of the discounted cash flows up to the end of the concession period in 2048.

4. The statistical methodology used in this analysis

In this analysis the quantities T, A and VOC are considered as continuous random variables of which samples are obtained in order to develop statistical distributions for further calculation. Clearly, in this project we are interested in the properties of the mean differences, their significance and their uncertainties. There are two well known approaches to the analysis of matched pairs which is the form of the sample sets of these variables. We can use tests which are largely free of the possibly invalid assumption of normality. Such a test is the non-parametric Wilcoxon test in which one uses the sign of the differences and additionally orders the magnitudes. The second type of test is a parametric test in which the actual sizes of the differences are used in the calculation. Lapin (1978) suggests that the choice of test should provide the lowest probability of incorrectly rejecting the null hypothesis $H_0$ and also that non-parametric methods are inferior to parametric methods in this respect.

Goodness of fit tests\(^5\) by the Kolmogorov-Smirnov (K-S) method (Lapin, 1978) involving the differences of matched pairs of the three variables, show that the differences are all normally distributed. As an example Appendix B shows in detail how the calculation is carried out for speed differences in the east flowing direction, although an automated version\(^6\) is available. Because the differences are all normally distributed, it is reasonable to use a parametric test such as the t-test\(^7\), to establish the significance of the mean differences and a confidence interval for each. However, there is an important caveat which should be noted in using the t-test. If the sample differences have different variances then the appropriate type of distribution is that of Behrens-Fisher as discussed by Kim and Cohen (1998). This is not the same as t-distribution and different tables are involved. However there is available a simpler approach to the problem than using Behrens-Fisher. An approximation to the t-distribution was devised by Satterthwaite (1946) who showed that its use is appropriate if a substantial increase is made to the number of degrees of freedom. This method has been successfully applied to the data in Tables 1, 2, 3 and 4 below and is illustrated in particular using the Tables 1 and 2 below.

5. Calculation of the travel time savings.

On a freeway there is obviously a very substantial variation in traffic speed over a 24 hour period. This variation can only be described statistically. The main determinant of speed is the traffic density\(^8\) or more precisely, the number of vehicles per lane per hour. The relationship between traffic density and speed is given in Austroads (1988). This relationship, particularly at low speeds and high

\(^5\) The Kolmogorov-Smirnov and Anderson Darling tests are both designed to detect departures from normality in a distribution. Anderson and Darling (1954) in their original paper tested a sample of 40 observations for normality using the K-S distribution. The use of their own method yielded the same conclusion of normality as did the K-S. However in terms of goodness-of-fit, the authors distinguished between the “power” of their test to fit the distribution more precisely near its “tails” compared to the K-S test. The authors remarked also that it appears difficult to find a general optimum weighting function. The K-S distribution has the advantage in this application that the optimum weighting occurs around the median. One can see the effect of this choice in Appendix B, Figure B.

\(^6\) The Statistica software available from Statsoft enables this calculation to be readily carried out.

\(^7\) Aitken (1944) discusses this matter in his classical text. For large samples the t-distribution converges to the normal distribution. Additional discussion about the appropriateness of the t-test is given later in this paper. In particular the effect of unequal variances is canvassed.

\(^8\) Traffic density is the generic term for maximum surface flow (MSF) used by Austroads (1988), and lane loading measured in terms of vehicles per lane per hour.
traffic density has been the subject of much research. Wright and Lupton (2001) have highlighted the uncertainty of the speed-density relationship and showed, for example, that in congested conditions the behaviour of traffic is best viewed as a series of transient events over short periods of time, that is, on a microscopic scale. The lack of a deterministic relationship at very low speeds is again emphasised at the macroscopic level: the depiction of the curve turning back on itself implying that an increase in flow causes an increase in speed is inexplicable. Yet, as shown by Brilon et al (2005) the turn back phenomenon apparently does exist at bottlenecks\(^9\). For the purposes of this analysis, the variation in speed \(V\) with traffic density \(X\) under congested conditions has been accommodated in a simple way by fitting a cubic curve to the Austroads data and making the curve asymptotic to a very low speed (5 km/h). This assumption at least is adequately concordant with actual observations on the roadway. This curve is shown in Figure 2. Its equation is:

\[
V = 97.02 - 0.004X - 1.8E-5 X^2 + 3.28E-9 X^3. 
\] (2)

Figure 2: Speed on the M2 Motorway as a function of the lane loading.

The next stage in the calculation was to derive a traffic volume versus time template. The general form of the template was established early in the operation of the motorway by manual counting at each hour over a 24 hour period during a weekday and the traffic volumes were adjusted for later years in accordance with the actual AADT observed in 2009. The template is shown in Figure 3 for both the east and west flowing traffic.

Figure 3: The traffic volume\(^10\) in one lane versus time at hourly intervals over one weekday

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9 Brilon et al have shown examples of this behaviour for two and three lane highways in the Cologne region of Germany.
10 This template relates to a typical weekday. During a weekend period, the variance of the traffic volumes over a 24 hour period is typically about half that observed during a weekday. The corresponding variation of speed is therefore less. The weekday traffic defines the maximum range of speed differences likely to be observed.
To obtain the group of 24 matched pair samples of speed, for the unwidened and widened road, the traffic density is reduced by a factor of 1.5 to account for the widening and the above calculations are repeated. The calculation of travel time savings depends on the speed differences on the widened and unwidened road. Calculations are carried out for both the east and west flowing traffic but for convenience in presentation only the eastern flows are referred to in the figures below.

**Figure 5(a):** Frequency distribution of speed differences on the unwidened compared to the widened road. A normal curve\(^{11}\) is fitted to the distribution (see Appendix B).

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\(^{11}\) The use of the term "normal" needs to be explained. In his survey of the variety of probability curves, Aitken (1944) dispelled the once prevalent idea that normality and symmetry were the rule and that skewness was an accident of sampling. He stated that:

Figure 5(b): The uncertainty in the speed differences on the unwidened compared to the widened road

“The role of the normal distribution in statistics is not unlike the straight line in geometry: and we do not force curves into the mould of the straight line. Skew distributions are in fact the predominant type, for skewness arises from Lexian variability or non-homogeneity, from Poissonian statistical rarity, from limitation in the number of causes of variation and from non-linear transformation of the scale” (Lexian means derived from a time series)

Aitken has demonstrated how skew distributions can be approximated by a normal curve together with additional functions of similar Gaussian type that involve moments about the mean. The overlaid curve shown in Figure 5(a) is the result of this fitting process and was carried out by a software program.
The probabilities in Figure 5(b) were calculated from tables of the normal distribution where the mean speed $\mu = 10.7$ km/hour and the standard deviation $\sigma = 12.5$ km/hour were derived from the data used in constructing Figure 5(a). The result emphasises the variability of the difference in speed in probabilistic terms on the unwidened compared to the widened motorway. For example, there is only an even chance ($p=50\%$) that this difference would exceed 10 km/hour. In calculating travel time savings this uncertainty is expressed below in a different way by calculating the 95% fiducial limits of the mean.

5.1 East flowing traffic-summary of results

<table>
<thead>
<tr>
<th></th>
<th>-95% fiducial limit of speed (km/h)</th>
<th>Mean speed (km/h)</th>
<th>+95% fiducial limit of speed (km/h)</th>
<th>Variance (km/h)$^2$</th>
<th>Standard error (km/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before widening</td>
<td>Time for 21 km = $21/64.9 = 0.32$ h</td>
<td>76.4</td>
<td>87.9</td>
<td>738.6</td>
<td>5.5</td>
</tr>
<tr>
<td></td>
<td>Time for 21 km = $21/76.4 = 0.27$ h</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>After widening</td>
<td>Time for 21 km = $21/80.8 = 0.26$ h</td>
<td>87.1</td>
<td>93.5</td>
<td>226.4</td>
<td>3.1</td>
</tr>
<tr>
<td></td>
<td>Time for 21 km = $21/87.1 = 0.24$ h</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

|                      | Time for 21 km = $21/93.5 = 0.22$ h |                   |                                     |                     |                       |
5.2 The statistical significance of the mean speed difference for east flowing traffic

The hypothesis is now tested that the difference in mean speeds as a result of the road widening is zero (the null hypothesis $H_0$). This is first carried out using the t-test.

\[
t = \frac{(87.1 - 76.4)}{\sqrt{(5.5^2 + 3.1^2)}} = 10.7/6.3 = 1.7, \text{ with } 24 - 1 = 23 \text{ degrees of freedom}.
\]

This value of $t$ is significant at the 5% level according to a one-tailed\(^{12}\) entry in the t-tables. We therefore reject the null hypothesis. Thus, there appears to be a statistically significant difference in the speeds on the widened road compared to the unwidened road.

However there is a need to repeat this test taking into account the non-homogeneity of variance as shown in Tables 1 and 2.

A summary of an extensive literature survey has shown that if each of the two normal distributions are derived respectively from sample sizes $n_1$ and $n_2$, with means $x_{m1}$ and $x_{m2}$ and variances $s_1$ and $s_2$, the quantity

\[
t' = \frac{(x_{m1} - x_{m2})}{S}; \text{ where } S = \sqrt{\left(\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}\right)}, \text{ and } s_1 \neq s_2, \text{ is not distributed as } t, \text{ but in accordance with the Behrens-Fisher distribution (Kim and Chen, 1998.)}\(^{13}\).
\]

However, there is a simpler approach available. According to some earlier work by Satterthwaite (1946)\(^{14}\), if an adjustment is made to the number of degrees of freedom, tables of the actual t-distribution can be used. The approximate number of degrees of freedom (df) was shown to be:

\[
df = \frac{S^4}{\left[\frac{s_1^2}{n_1}\right]^2/(n_1 - 1) + \left[\frac{s_2^2}{n_2}\right]^2/(n_2 - 1)}.
\]

Applying this expression to the data shown in tables 1 and 2,

$s_1^2 = 738.6 \text{ kph}^2$ (speed variance of east flowing traffic on unwidened road),

$s_2^2 = 226.4 \text{ kph}^2$ (speed variance of east flowing traffic on widened road).

$n_1 = n_2 = 24$

$S = 1.657E3 \text{ kph}$

$df = 36$ whereas previously $df = 24 - 1 = 23$.

The t-test with 36 degrees of freedom gave $t = 1.69$ which is significant at the 5% level, and with 24-1 degrees of freedom, $t = 1.71$, which is slightly more significant at the 5% level. It would appear that the t-test is confirmed in its robustness in this application and the non-homogeneity of variance is not an issue in this particular application. Similar results are relevant for the other tables and there is no need to repeat the type of the calculation.

In summary, the differences in travel time and their fiducial limits over a 21 km transit are

\(^{12}\) A two-tailed test would have avoided the need to consider the direction of the change. But the direction is obvious here so a one-tailed test is appropriate.

[0.06, 0.03, 0.02] hours. These differences are used to obtain the values of the travel time savings by adopting an appropriate factor for the value of time as discussed below. The west flowing traffic is considered next in a similar manner.

### 5.3 West flowing traffic- summary of results

#### Table 3: before widening

<table>
<thead>
<tr>
<th>-95% fiducial limit of speed (km/h)</th>
<th>Mean speed (km/h)</th>
<th>+95% fiducial limit of speed (km/h)</th>
<th>Variance (km/h)^2</th>
<th>Standard error (km/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>63.1</td>
<td>74.9</td>
<td>86.7</td>
<td>777.76</td>
<td>5.7</td>
</tr>
<tr>
<td>Time for 21 km = 21/63.1 = 0.33h</td>
<td>Time for 21 km = 21/74.9 = 0.28h</td>
<td>Time for 21 km = 21/86.7 = 0.24h</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Table 4: after widening

<table>
<thead>
<tr>
<th>-95% fiducial limit of speed (km/h)</th>
<th>Mean (km/h)</th>
<th>+95% fiducial limit of speed (km/h)</th>
<th>Variance (km/h)^2</th>
<th>Standard error (km/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>80.6</td>
<td>86.7</td>
<td>92.8</td>
<td>207.46</td>
<td>2.9</td>
</tr>
<tr>
<td>Time for 21 km = 21/80.6 = 0.26h</td>
<td>Time for 21 km = 21/86.7 = 0.24h</td>
<td>Time for 21 km = 21/92.8 = 0.23h</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### 5.4 Statistical test of significance for the speed difference for west flowing traffic

Again, \( t = (86.7 - 74.9) / \sqrt{(5.7^2 + 2.9^2)} = 11.8 / 6.4 = 1.84 \). The null hypothesis is rejected as tables of the \( t \)-distribution show that with 23 degrees of freedom, \( p < 0.05 \). (\( t = 1.71 \) for \( p = 0.05 \)). The speed difference is therefore statistically significant. The range of travel time differences for the western traffic is therefore [0.07, 04, 01] hours.

### 6. Valuation of travel time savings (T) on the widened road compared to the unwidened road

The travel time differences are now used to obtain values of travel time savings. At the outset, it should be noted that we are dealing here with an economic anomaly in that there is no market for travel time savings. Generally, the translation of travel time savings into financial gain is not readily determined and the values determined in CBA are notional. Moreover, as shown by Horowitz (1978) the value of travel time is subjective. In other words, the conditions of travel play a very significant role in the motorist's perception of the value of time. Time spent in congested traffic conditions is accorded a much greater value than a journey conducted in entirely free flowing traffic. Abelson (1986) estimated the value of time spent in a journey to work in congested conditions was rated three times greater than the same time spent in a trip in moderate traffic. A more recent finding on the value of time was developed by Masson Wilson Twiney (2000) in their predictions for the Cross City Tunnel.
Based on extensive surveys they came to the conclusion that the total value of time corresponded to 4.3 minutes per dollar, or 23.3 cents/minute\(^\text{15}\) which according to the authors:

“is consistent with recent experiences in calibrating transport network models to reflect route choices for existing tollways in Sydney”.

This value of time will be adopted in this analysis.

### 6.1 Value of (T) for east flowing traffic

The range of travel time differences is \([0.06, 0.03, 0.02]\) hours.

The mean value is 0.03 hours = 1.8 minutes. Assuming that there are 48372 vehicles/day\(^\text{16}\), the annual saving = \(48372 \times 365 \times 1.8 \times 0.233 = $7.4\) million.

### 6.2 Value of (T) for west flowing traffic

The range of travel time differences is \([0.07, 0.04, 0.01]\) hours.

The mean value is 0.04 hours = 2.4 minutes. The annual saving is \(48372 \times 365 \times 2.4 \times 0.233 = $9.87\) million.

### 6.3 Total value of (T) and its fiducial limits.

The total annual TTS for both directions is thus \($(7.4 + 9.9) = $17.3\) million.

The standard error of the sum is 0.02 hours and the corresponding fiducial limits are \(\pm 0.041\) hours \((0.02 \times 2.069)^{17}\). The corresponding value of this fiducial limit is \($10.2\)m. The confidence interval is thus:

\[
[(17.3 + 10.2)\ m, 17.3\ m, (17.3 - 10.2)\ m].
\]

The inflation adjusted present values of travel time savings are summarised in Table 5.

<table>
<thead>
<tr>
<th>Discount rate</th>
<th>PV of lower (T)</th>
<th>Mean (T)</th>
<th>PV of upper (T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.7%pa</td>
<td>$58.9\ m</td>
<td>$143.6\ m</td>
<td>$228.3\ m</td>
</tr>
<tr>
<td>Inflation adjusted ((\times 1.31))</td>
<td>$77.1\ m</td>
<td>$188.1\ m</td>
<td>$299.1\ m</td>
</tr>
</tbody>
</table>

### 7. Estimates of the reduction in accident costs due to increases in road capacity

To the author’s knowledge there does not appear to have been any systematic Australian studies of the effect of increased road capacity on accident rates. The NSW Roads and Traffic Authority have data bases for accident rates on principal urban roads but these results have not been

\(^{15}\) For AM and PM peak travel, the authors gave the value of time as 16.6 cents per minute. Between peak travel, the value of expected time is 4.6 cents per minute.

\(^{16}\) This figure which applied in 2009 will be adopted as the appropriate traffic volume on the M2 in the east and west directions of flow.

\(^{17}\) From tables of the distribution, 2.069 is the two-tailed value of \(t\) for 23 degrees of freedom.
specifically related to road capacity so as to generate a cause and effect relationship. However, in the United States, the Federal Highway Administration (FHWA, 2005) has reported some findings on the results of converting a four lane highway to five lanes in one direction. At 79 freeway sites it was found that the conversion caused a statistically significant increase in accident rates. This increase was attributed to an increase in rear end collisions and sideswipe accidents. However, the percentage change in accident frequency was significantly reduced when the conversion was from 5 to 6 lanes. The authors suggest that at least for the five to six lane conversions:

“the effect of the project may have been to dissipate congestion upstream of the treatment site by removing the treatment site as a bottleneck”. 

It appears that accident rates may be reduced if there was less congestion, an intuitively appealing idea.

7.1 Expected crash rates on the M2 Motorway before and after widening

A statistical correlation analysis of crash data\(^ {18}\) from the M2 Motorway over the period 1997 to 2008 suggests that the crash rates (defined as crashes per day) are proportional to the vehicle-km of travel (VKT) per day, so that by reducing VKT (by reducing the number of vehicles per lane) and thus sharing the traffic among more lanes will reduce the accident rates. The correlation function is given by

\[
\text{Crashes/day/lane} = -0.0127 + (8.4463 \times 10^{-8}) \cdot \text{VKT} 
\]  
(Pearson R = 0.81) \hspace{1cm} (3)

**Figure 6.** The regression line between crash rates per lane and VKT per lane.

Equation (3) is used to predict the crash rates per lane when the number of lanes is increased from four to six. The differences between the crash rates are then calculated and the frequency distribution

\(^{18}\) Only the RTA data for injury crashes was used for this analysis. Between 1997 and 2008 there was a total of 968 crashes of which 328 or 33.9% of the total were classified as injury crashes.
of the differences obtained. The use of a normal probability function for the differences is supported by applying the K-S method (D = 0.131, p<0.05) and therefore the population from which the sample was drawn can be considered normal. Therefore a t-test of the difference of the means is appropriate. The null hypothesis is that the difference is not significant. The test results are as follows.

7.2 Calculation of the difference in accident costs (A) on the widened compared to the unwidened road

For the unwidened road, the mean (crash rate/lane) = 0.019, standard error = 0.0025.

For the widened road mean (crash rate/lane) = 0.008, standard error = 0.0014.

Difference of the means = 0.011, standard error = 0.003.

Therefore t = 0.011/0.003 = 3.7. From t tables t = 1.796 for 11 degrees of freedom (for a one-tailed test) and therefore the value of t=3.7 implies that the difference of the means is very significant. The null hypothesis is therefore rejected.

The mean change (reduction) in total crashes per year for 6 lanes is 0.011 x 365 x 6.0 = 24.

According to BITRE (2006), applying its results to a typical population, 12.6% or 3 of these 24 crashes would be classified as hospitalized injured and 87.4% or 21 of these 24 crashes would be classified as non-hospitalized injured.

The cost of the hospitalized injured would be $214 000 and the cost for the non-hospitalized injured would be $2100. The total weighted mean cost per crash is therefore:

\[(3 \times 214,000 + 21 \times 2100)/24 = ($642 000 + $ 44 000)/24 = $28,587\]

7.3 Fiducial limits of the costs.

The upper fiducial limit for total crashes per year for 6 lanes = (0.011 + 2.201 x0.003) x365x6 = 38.5.

The lower fiducial limit for total crashes per year for 6 lanes = (0.011–2.201x0.003) x365x6 = 8.54.

The confidence interval for the costs is:

\[[8.54 \times$ 0.003m, 24.0 \times$0.003m, 38.5 \times$0.003m] = [$ 0.03m, $ 0.072 m, $0.116m],\]

In terms of present values over 36 years and using equation (1), table 6 below shows the inflation adjusted present values.

<table>
<thead>
<tr>
<th>Discount rate</th>
<th>PV of lower fiducial limit of cost reduction</th>
<th>PV of mean cost reduction</th>
<th>PV of upper fiducial limit of cost reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.7%pa</td>
<td>$0.25m</td>
<td>$0.598m</td>
<td>$0.963m</td>
</tr>
<tr>
<td>Inflation adjusted PV (×1.09)</td>
<td>$0.273m</td>
<td>$0.652m</td>
<td>$1.045m</td>
</tr>
</tbody>
</table>

Table 6: inflation adjusted present values of accident cost reduction
8. Vehicle operating costs (VOC)

Abelson (1986) pointed out that the evaluation of VOC is influenced by many factors such as type of vehicle and road conditions which vary geographically; estimates of costs are said to involve about 20 parameters. Abelson used NAASRA data to develop a relationship between estimated vehicle costs and speeds on freeways. This relationship between VOC and speed V is U-shaped: VOC first decreases and then increases with speed. The following quadratic function has been fitted to Abelson’s data:

\[
VOC = 10.174 - 0.092 V + 0.001 V^2 \tag{4}
\]

Figure 7: The relationship between vehicle operating costs and speed.

Equation (4) has been used by the author to evaluate differences in VOC both for east and west traffic flows which would occur if the road was widened. For example, in the easterly flowing direction the change in VOC (ΔVOC) with speed change ΔV is:

\[
\Delta VOC = 0.028 - 0.152 \Delta V + 0.012 \Delta V^2 - 0.0005 \Delta V^3 + 8.642E-6 \Delta V^4 \tag{5}
\]

The graph of this function in Figure 8 shows how a change in speed can change the operating costs from positive to negative.
Figure 8: Change in VOC versus change in speed

![Graph showing change in VOC versus change in speed](image)

Table 7: the calculations of VOC

<table>
<thead>
<tr>
<th>Mean change in VOC</th>
<th>Standard error</th>
<th>Kolmogorov-Smirnov test for normality</th>
<th>Students “t”</th>
<th>Significant difference?</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.28 cents/km (east)</td>
<td>0.15 cents/km</td>
<td>d = 0.28, p &lt; 0.05</td>
<td>1.83 (23 degrees of freedom)</td>
<td>yes</td>
</tr>
<tr>
<td>-0.28 cents/km (west)</td>
<td>0.14 cents/km</td>
<td>d = 0.22, p &lt; 0.05</td>
<td>2.0 (23 degrees of freedom)</td>
<td>yes</td>
</tr>
</tbody>
</table>

The standard error of the sum of the means = 0.204,

The confidence interval for the sum of the means is:

\[ -0.56 + 2.07 \times 0.204, -0.56, -0.56 - 2.07 \times 0.204 = [-0.14, -0.56, -0.98]. \]

Translating this confidence interval into inflation adjusted values\(^{19}\), we have:

Upper fiducial limit = \(2.3 \times -0.14 \times 48372 \times 365 \times 21 / 100 = -$1.2m\)

Mean = \(2.3 \times -0.56 \times 48372 \times 365 \times 21 / 100 = -$4.78m;\)

Lower fiducial limit = \(2.3 \times 0.98 \times 48372 \times 365 \times 21 / 100 = -$8.36m.\)

The confidence interval in terms of present values is \([-9.96, -39.6, -69.3]m.\)

---

\(^{19}\) The Abelson data was developed in 1984. Reserve Bank of Australia figures on inflation rates would increase the data by a factor of 2.3 in order to calculate the costs in 2009 dollars.
9. Overall results and conclusions about the widening proposal from the cost benefit analysis

Table 8: summary of the CBA

<table>
<thead>
<tr>
<th>The quantity after widening</th>
<th>Mean present value (inflation adjusted) ($m)</th>
<th>Lower fiducial limit ($m)</th>
<th>Upper fiducial limit ($m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Travel time savings</td>
<td>188.1 (a)</td>
<td>77.1</td>
<td>299.1</td>
</tr>
<tr>
<td>Accident cost savings</td>
<td>0.65 (b)</td>
<td>0.27</td>
<td>1.05</td>
</tr>
<tr>
<td>Vehicle operating costs&lt;sup&gt;20&lt;/sup&gt;</td>
<td>−39.6 (c)</td>
<td>−8.36</td>
<td>−69.3</td>
</tr>
<tr>
<td>Construction cost</td>
<td>550 (d)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The main contributions to the net present value of the project are (a), (c) and (d).
Thus the mean NPV = (a) + (c) − (d) = − $402 million. The 95% confidence interval for the mean is found by combining the variances of (a) and (c). The resulting confidence interval is:

$$[-516m, -402m, -287m].$$

As the mean NPV and its fiducial limits all have large negative values implying economic loss, it is concluded that the widening proposal is not economically viable. The official view that an economic reason exists cannot be supported. A determination to proceed would therefore be a contravention of the Environmental Planning and Assessment Regulation 2000. Moreover from a financial viewpoint, to proceed would also represent a serious misallocation of capital.

In terms of the more conventional benefit to cost ratio (BCR), the BCR lies within the 95% confidence interval [ 0.13, 0.27, 0.42 ]. In the environmental impact statement (Transurban, 2010) produced on behalf of the proponents Transurban and the NSW Roads and Traffic Authority, a value of BCR = 3.4 was claimed without any uncertainties. The difference in the mean values is a factor of 12.6 times. Such a gross discrepancy suggests bias and predetermination to favour the project in order to justify the claim that the project is “critical infrastructure”.

From the legal viewpoint, it is of interest to note that according to section 75T of the Act, the term “critical infrastructure” implies that there can be no objector appeal against determination. However, for the proponents to claim that the infrastructure is critical, it has to be shown to be economic. What we are seeing here in this proposal is an attempt by a government department the NSW Roads and Traffic Authority to evade its responsibilities under the Act on behalf of the financial future of the toll road owner and operator Transurban.

From a socio-economic viewpoint the failure of the proposal to provide any substantial reduction in the cost of accidents is of major concern. Transurban has stated that increasing the traffic to increase toll revenue is one of the main aims of the proposal.<sup>21</sup> It will certainly achieve this aim through the uncontrollable effect of traffic induction. As shown in Figure 1 congestion caused deterioration of the economic value of the facility to toll-paying motorists less than 5 years from the start of operation of the M2 in 1997.

References

<sup>20</sup> The likely explanation for the negative signs is that speeds would be greater on the widened road and therefore the “savings” become costs.

<sup>21</sup> Rebecca Urban (The Weekend Australian, May15-16, 2010). “Toll road chief faces investor ire”.

Aitken, A. C. (1944) Statistical Mathematics (Oliver and Boyd, Edinburgh)


Appendix A

The derivation of the factors relating the AM peak traffic the average annual daily traffic (AADT) for the M2 Motorway.
This appendix describes the general statistical method used to derive the factors and their uncertainties that relate the AM peak traffic volumes to the average annual daily traffic (AADT). This method was applied to the M2 Motorway which was under construction in 1996. Traffic census records derived by the NSW Roads and Traffic Authority (RTA) provided the data used in the derivation. The results of this investigation leave little doubt that the forecasts of the level of service on the M2 made in 1994 were grossly in error and the proposed widening of the M2 is clearly an attempt to compensate for this error.

1. Details of the derivation

Figure A1 shows the route of the M2 (F2 East) in dotted lines in relation to six of the roads that were expected to be the sources of traffic using it when it became operational.

Figure A1: the route of the M2 showing the feeder roads in the catchment

The traffic volumes using these six roads are described in the RTA publication: “Traffic volume data for the Sydney Region (1996)”. The RTA data are the official source of traffic statistics for NSW. The six roads are Epping Road, Lane Cove Road, Copeland Road, Castle Hill Road, Pennant Hills Road and Beecroft Road. Other roads in the region will contribute traffic but a sample of six is considered sufficient to illustrate the method of calculation and to derive a measure of the uncertainty.

of the factors. The traffic volumes on Epping Road, the main distributive highway in the region, will be used to illustrate the general method of calculating the AM peak factors. Epping Road runs almost parallel to the route of the M2 (F2 East)\(^{22}\).

Figure A2 shows graphically the average daily traffic volumes on Epping Road at one hour intervals (commencing at midnight) for the week commencing 12/08/96. The graph was constructed from the data given at page 370, Reference 1. The similarity to the M2 template in Figure 3 should be noted.

![Figure A2: hourly distribution of traffic volumes on Epping road](image)

2. The detailed derivation of AM peak factors for Epping Road

The graph of Figure A2, which was derived from the RTA traffic census records shows that the AM peak traffic occurs on Epping Road, as it does on the M2 east during the two hour period 7 AM to 9 AM in both the easterly and westerly directions. Note that the AM peak period extends over two hours not one hour. For some roads such as Pennant Hills Road the traffic flows North-South but the peak period remains defined in the same way.

Weekday traffic averages are:
(i) Traffic proceeding east 7-8 AM = 3840 vehicles,
(ii) Traffic proceeding east 8-9 AM = 3638 vehicles,

Total vehicles proceeding east during the two-hour period = 7478.

---

\(^{22}\)In RTA nomenclature, “F” is used to denote a freeway, “M” is used to denote a tolled road. The F2 route did not become a tollway until it was operational.
The average annual daily traffic volume for easterly flow = 29450 vehicles according to the RTA data (page 210).

Therefore, the conversion factor $F_e = \text{AADT} / \text{AM Peak 2 hour flow} = 29450 / 7478 = 3.94$.

Applying the same reasoning to the AM traffic proceeding west.

(i) Traffic proceeding west 7-8 AM = 1449 vehicles 
(ii) Traffic proceeding west 8-9 AM = 1626 

Total vehicles proceeding west = 3125

Again, the AADT volume as recorded in the RTA data (page 211) for westerly flow is 28690 vehicles.

The conversion factor $F_w = 28690 / 3125 = 9.18$.

Using the same method as for Epping Road we now calculate the peak AM factors derived for five other selected roads in the M2 catchment. All results are summarized in Table A1 below.

<table>
<thead>
<tr>
<th>Road</th>
<th>RTA reference</th>
<th>Direction</th>
<th>AM Peak 2 hour factor $F$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epping Road</td>
<td>74.062</td>
<td>E</td>
<td>3.94</td>
</tr>
<tr>
<td></td>
<td></td>
<td>W</td>
<td>9.18</td>
</tr>
<tr>
<td>Lane Cove Road</td>
<td>52.014</td>
<td>N</td>
<td>7.17</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S</td>
<td>4.29</td>
</tr>
<tr>
<td>Copeland Road</td>
<td>74.439</td>
<td>E</td>
<td>3.31</td>
</tr>
<tr>
<td></td>
<td></td>
<td>W</td>
<td>9.08</td>
</tr>
<tr>
<td>Castle Hill Road</td>
<td>72.022</td>
<td>E</td>
<td>5.09</td>
</tr>
<tr>
<td></td>
<td></td>
<td>W</td>
<td>6.97</td>
</tr>
<tr>
<td>Pennant Hills Road</td>
<td>74.087</td>
<td>N</td>
<td>6.28</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S</td>
<td>6.19</td>
</tr>
<tr>
<td>Beecroft Road</td>
<td>74.452</td>
<td>N</td>
<td>9.56</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S</td>
<td>4.70</td>
</tr>
</tbody>
</table>

### 3. Summary of findings

The mean values of the AM 2 hour peak to AADT conversion factors are shown in Table A2 together with their 95% fiducial limits.
Table A2

<table>
<thead>
<tr>
<th>Travel direction</th>
<th>Upper 95% fiducial limit</th>
<th>Mean</th>
<th>Lower 95% fiducial limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>East/South</td>
<td>5.64</td>
<td>4.59</td>
<td>3.53</td>
</tr>
<tr>
<td>North/West</td>
<td>9.5</td>
<td>8.04</td>
<td>6.6</td>
</tr>
</tbody>
</table>

The statistical results shown in Table A2 suggest that there would be only a 5% probability that the factor of six used by the M2 consultant could have arisen from investigations of the traffic feeding the M2 catchment.

Reference

Appendix B
The Kolmogorov-Smirnov (K-S) test of normality for the speed differences in the easterly direction.

The Kolmogorov-Smirnov test compares the observed cumulative frequency distribution derived from the sample with that expected from the population. One observes the maximum deviation between the observed and expected values. Tables of the distribution allow the significance of these deviations from normality to be tested against tabulated values to obtain a probability (say 0.05) that the observed distribution is the same as that expected (the null hypothesis). Table B sets out in detail the calculations needed to test whether there is a significant enough difference to reject the null hypothesis of normality. It will be recalled that the mean speed difference $\mu = 10.7\ \text{km/hour}$, and the standard deviation $\sigma = 12.5\ \text{km/hour}$.

<table>
<thead>
<tr>
<th>Speed difference boundary (km/h)</th>
<th>Normal variate $(X - \mu) / \sigma$</th>
<th>Expected frequency $X$</th>
<th>Expected cumulative count</th>
<th>Observed cumulative count</th>
<th>% observed cumulative count</th>
<th>% expected cumulative count</th>
<th>Expected minus observed count</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\leq 0$</td>
<td>-0.861</td>
<td>0.1949</td>
<td>0</td>
<td>0</td>
<td>19.49</td>
<td>0.195</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>-0.461</td>
<td>0.3228</td>
<td>10</td>
<td>41.7</td>
<td>32.28</td>
<td>-0.094</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>-0.059</td>
<td>0.4761</td>
<td>15</td>
<td>62.5</td>
<td>47.61</td>
<td>-0.149</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>+0.342</td>
<td>0.6331</td>
<td>19</td>
<td>79.2</td>
<td>63.31</td>
<td>-0.159</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>+0.743</td>
<td>0.7704</td>
<td>20</td>
<td>83.3</td>
<td>77.04</td>
<td>-0.063</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>+1.144</td>
<td>0.8729</td>
<td>21</td>
<td>87.5</td>
<td>87.29</td>
<td>-0.002</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>+1.545</td>
<td>0.9394</td>
<td>21</td>
<td>87.5</td>
<td>93.94</td>
<td>+0.052</td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>+1.947</td>
<td>0.9744</td>
<td>22</td>
<td>91.7</td>
<td>97.44</td>
<td>+0.055</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>+2.210</td>
<td>0.9864</td>
<td>23</td>
<td>95.83</td>
<td>98.64</td>
<td>+0.028</td>
<td></td>
</tr>
<tr>
<td>45</td>
<td>+2.750</td>
<td>0.9970</td>
<td>24</td>
<td>100.0</td>
<td>100.0</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

The critical deviation value $D$ for $n = 10$ is 0.369 ($p < 0.05$). But the maximum observed value of $D = 0.195$. Therefore as the null hypothesis is that the distribution is normal, we accept the hypothesis at the 5% level of probability. The result of the K-S test are graphically summarised in Figure B.
Figure B: showing the deviations from normality

![Graph showing deviations from normality](image)

End note

**Corrigenda**

The following corrections were incorporated into the text on 14 July, 2011.

On page 2: Introduction: the background to the M2 widening proposal… Kenneally has been replaced by **Keneally**

On page 18, Table 8:
**Accident cost savings** Mean present value ($m) (inflation adjusted) **0.65 (b) replaces 0.27 (b)**
Lower fiducial limit ($m) **0.27 replaces 0.65.**

I certify that these corrections were carried out by me personally
(sgd) Dr John L Goldberg
Formerly Honorary Associate
Faculty of Architecture Design and Planning
The University of Sydney