ESTIMATING PASSING DEMAND

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Abstract

Nearly all of New Zealand's strategic routes have been built as two-lane highways, often through mountainous and rolling country. Increasing traffic flows have increased the demand for passing lanes to increase passing opportunities for users.

Currently in New Zealand, passing lane benefits are assessed using two methods. For complex or expensive projects, computer micro-simulation of passing lane options is used. For projects with a lower capital cost or preliminary assessments of major projects, a simplified procedure is used. This research involved evaluating the simplified procedure for estimating passing demand.

It was found that the equations in the simplified procedure for estimating passing demand between two streams has a critical flaw that occurs when the standard deviation of the speeds of the faster stream is low, causing the equations to estimate near zero passing demand when some demand would in fact exist.

Additionally, probability distributions were fitted to actual speed data, and these distributions were used in a simple simulation model, to represent the speeds of vehicles in the two traffic streams. It was found that the logistic (not the Normal) distribution produced the best fit to the speed data. It was found that using these speed distributions in the simple simulation model, it is unnecessary to consider two separate traffic streams (e.g. cars and trucks) as required in the simplified procedure.

1. Introduction

The Project Evaluation Manual (Transfund, 1999) describes two procedures for evaluating passing lanes; the TRARR computer simulation software developed by the Australian Road Research Board (ARRB) and a simplified procedure.

The simplified Project Evaluation Manual (PEM) procedure can be used to assess the benefits of passing lanes projects not involving realignments, not involving multiple passing lanes, and with a capital cost less than $400 000. It can also be used as a tool for identifying potentially worthwhile passing lane projects, before a more detailed and therefore more costly TRARR simulation analysis is carried out. There is also a revised simplified procedure under trial by Transfund, that simplifies the analysis further and enables analysis of passing lane strategies.

This paper investigates one aspect of the simplified method (the estimation of passing demand), based on a method proposed by Troutbeck (1982). Troutbeck's method was also used in developing the revised simplified method currently under trial. A detailed description of the research reported here is given in Roozenburg (2004).

2. Simplified Procedure for Assessment of Passing Lanes

The PEM's simplified procedure is for use in a limited set of circumstances. It is important to have a good understanding of the procedure, in order to identify when it is appropriate to use it, and this section discusses the simplified procedure.

In the assesment of the benefits of passing lanes, the travel time "lost" when following (because passing is not appropriate) is of critical importance in the evaluation of passing lane benefits. In the simplified procedure the Percentage of Time Spent Following (PTSF), that is, the amount of time spent waiting to pass is assessed through the Accrued Passing Demand (APD). The APD is summed over the analysis length to produce an Overall Passing Demand (OPD), which is then converted to the average time lost for all vehicles travelling at less than their desired speed to determine travel costs. The simplified procedure assumes that the APD (overtakings/h) is generally proportional to the level of bunching (or platooning) of the traffic flow, as follows (Koorey and Gu, 2001):

$$\mathrm{APD} = \{\%Bunching\} \times \{One\text{-}Way\text{-}Volume\} \tag{1}$$

The APD can then be used to find the Average Distance Spent Following (ADSF), which is the area under a plot of the APD divided by the traffic volume (i.e. the percent following), as follows:

$$ADSF = \int_0^{AnalysisLength} \%Following \tag{2}$$

The PTSF is found graphically, by dividing the ADSF by the distance along the analysis length. It has been found however that the level of bunching approximates PTSF fairly well, with Harwood et al. (1999) finding that using a 3 second headway when measuring bunching in the field produces the best estimate of PTSF.

Unfortunately bunching data is not always readily available or economic to collect, therefore the simplified procedure provides for an alternative method for determining APD and subsequently PTSF. This involves preferably having a starting point for the survey where bunching data is available and then estimating the initial APD, using speed data.

The level of APD throughout the survey length is found by first dividing the survey length into segments, each segment having much the same alignment characteristics throughout (to ensure a reasonably constant speed within each section). For each segment the mean and standard deviation of the free speed of all free-flowing vehicles for both streams (typically, car and truck streams) need to be obtained. The hourly traffic flow data then needs to be examined to determine the time periods to be considered, so that the average hourly one-way flows for cars and trucks can be determined.

Using this information on the traffic characteristics, total passing demand can be determined. The PEM procedure for estimating the total passing demand involves summing the passing demand for cars passing cars, cars passing trucks and trucks passing trucks. This total passing demand forms the demand part of the demand-supply relationship for passing opportunities, and is estimated as follows:

$$D_{total} = D_{car\text{-}car} + D_{car\text{-}truck} + D_{truck\text{-}truck} \qquad (3)$$

The supply part of the demand-supply relationship for passing opportunities is found by multiplying together the Proportion of Available Gaps (PAG) in the opposing traffic stream, the Proportion of Adequate Sight Distance (PASD) for passing for the section of road (determined from the road geometry), and the estimated maximum possible overtaking rate for a section of road with no oncoming traffic (108 overtakings per kilometre per hour), as follows:

$$S = PAG \times PASD \times 108 \qquad \text{(overtakings/km/h)} \qquad (4)$$

Using the calculated supply and demand of passing opportunities, the net amount of desired passing not achieved per hour per kilometre for each section can be estimated. This is known as the Unsatisfied Passing Demand (UPD) and is estimated as follows:

$$UPD = D - S \qquad \text{(overtakings/km/h)} \qquad (5)$$

Where the UPD is negative, this indicates that previously built up passing demand is able to be dissipated. From the UPD for each option and each time period, the overall passing demand can be determined. Therefore the total number of impeded vehicles is expected to accrue (or dissipate) linearly along the road, giving an Accrued Passing Demand (APD), which is the same APD as would be found from a bunching survey. Where a new road segment occurs, the UPD per kilometre changes accordingly. Passing lane options can then be compared by looking at the changes in the Overall Passing Demand (OPD) between different options, where the OPD is the integral of APD over the running distance.

In the simplified procedure, Unsatisfied Passing Demand (UPD) is currently estimated for each road segment. This is then added to the existing Accrued Passing Demand (APD). For a given road section, the UPD currently does not vary with respect to the prior passing demand, with the exception that the APD cannot fall below zero. When comparing passing lane options, this therefore generally leads to parallel changes in the APD following a passing lane, with the two options never meeting. This clearly would not be the case, as it is unlikely that the passing lane would still be having a significant effect on APD some distance downstream.

Koorey and Gu (2001) proposed to solve this problem by pointing out that only lead-vehicles or free vehicles will dictate vehicle interactions when vehicles are bunched. The vehicles already bunched are not adding additional passing demand in the sense of demand used here, where demand is the number of vehicles that they would pass if given the opportunity. Therefore, the queued vehicles could be ignored in a passing demand calculation, provided that we also ignore within-queue interactions.

Koorey and Gu (2001) propose that the proportion of catch-ups should logically decrease as the proportion of bunched vehicles increases. Therefore, for a given percent following (f), there are $\{(1\text{-}f) \times Volume\}$ vehicles free to interact. The calculated passing demand is hence $\{(1\text{-}f) \times D_{A\text{-}B}\}$, where $D_{A\text{-}B}$ is the passing demand for vehicles in stream A to pass vehicles in stream B. If we assume (as the simplified procedure does) that the APD is proportional to bunching and volume, then the true passing demand can be estimated as follows:

$$\{\text{True Demand}\}_{A\text{-}B} = (1\text{-APD}/\{\text{One-Way-Volume}\})\times D_{A\text{-}B} \tag{6}$$

The result of this approach is that at relatively high levels of APD, the additional demand generated by a lack of passing opportunities is much lower than the additional demand generated at much lower levels of APD, where bunching is minimal over the same road segment. This results in a road segment, with a passing lane which will substantially lower the APD, having a quicker return to a higher APD downstream than the same road segment without the passing lane. This leads to the APD plots converging at some point downstream for the passing lane options, rather than APD plots continuing on parallel to each other (as in the current demand formulation). This convergence is illustrated in Figure 1.

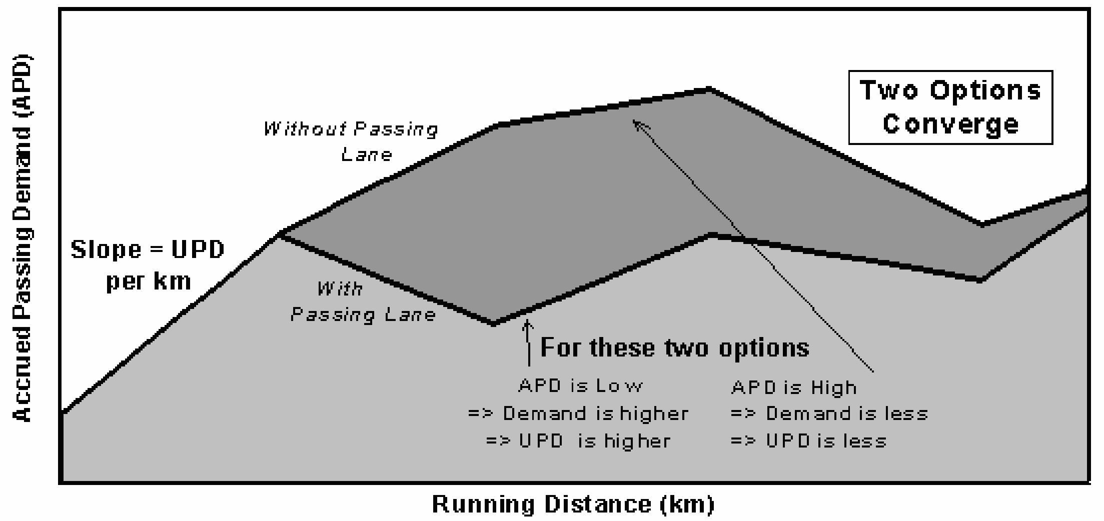

Figure1: Schematic diagram of APD adjusted for initial APD
(from Koorey and Gu, 2001)

Let us now consider how “passing demand” is estimated. The generalised passing demand, $D_{A\text{-}B}$, (i.e. the frequency with which vehicles in stream A catch up to vehicles in stream B, or catch-ups/km/h) is estimated as follows:

$$D_{A\text{-}B} = \gamma \times K_A \times K_B \times s_A \tag{7}$$

where:

γ = a parameter, based on the difference in the mean speeds of the two streams, A and B, and the ratio of the standard deviations of the streams (from PEM Table 10.1);

K = traffic density (veh/km) = *{Hourly Flow}* / *{Mean Speed}*;

s_A = standard deviation of speed for stream A (km/h).

In the above equation γ is found from tables using the two following equations

$$X = \frac{(\bar{v}_A - \bar{v}_B)}{s_A} \tag{8}$$

$$Y = \frac{s_A}{s_B} \tag{9}$$

where $\bar{v}_A$ and $\bar{v}_B$ are the mean speeds for stream A and B respectively, and s_B is the standard deviation of speed for stream B.

In the simplified procedures, the two streams are generally “cars” and “trucks”, but equation 7 can be simplified to estimate catch-ups within streams (e.g. faster cars catching up with slower ones). When a vehicle catches up to a slower one, it is assumed that the driver of the former will wish to pass, because of a higher desired speed. This represents the within-stream passing demand (overtakings/km/h) and can be estimated using the following equation (Wardrop 1952):

$$D_{A-A} = 0.564 K_A^{\ 2} s_A \tag{10}$$

3. Passing Demand Model in Excel

It is interesting that equation 7 does not include the standard deviation of stream B speeds (s_B). Although s_B is a factor in determining γ and hence is taken into account when determining passing demand, equation 7 shows the passing demand would approach zero as s_A approaches zero. This apparent illogicality was the initial reason for the investigation of the validity of the equations for estimating passing demand.

To enable an investigation into the validity of the PEM passing demand equations, a simple Excel-based simulation model, to analyses the ordering of vehicles entering and leaving a section of road, was developed. This model produces probability distributions for passing demand.

This model was based on assumptions similar to those underlying the PEM equations (e.g. vehicles having constant speeds within sections and vehicle passing slower vehicles they catch up with if the conditions allow. The model also assumed that if there was a section of road and vehicles could be uniquely identified entering and leaving the section over a set period of time, then it could be determined whether a vehicle has passed another vehicle (as shown in Figure 2).

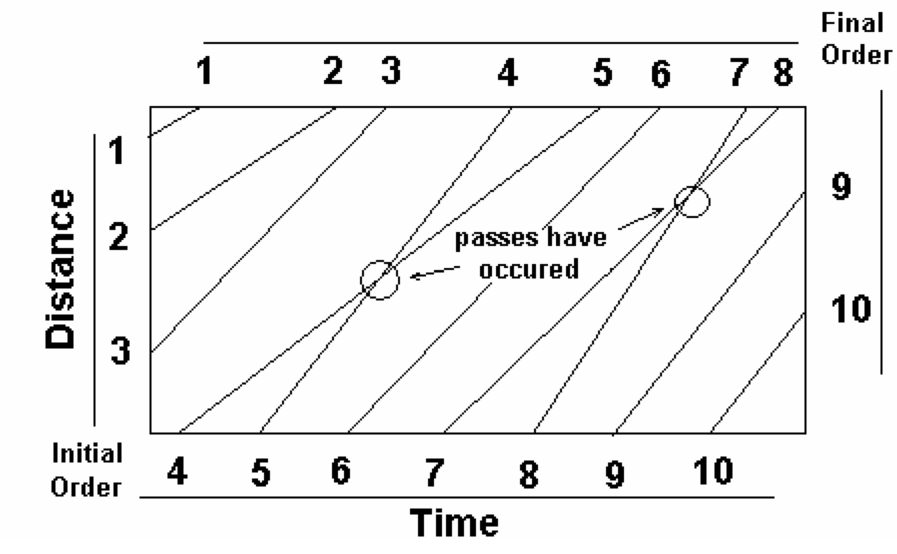

Figure 2: Space-Time Plot Showing Initial and Final Order of Vehicles.

In this model each vehicle stream was given different speed characteristics, with the probability distributions for speed being able to be varied via changes to the distribution parameters (e.g. the mean and standard deviation). The initial headway distribution of vehicles entering the section could also be varied, but in keeping with the assumption of unimpeded flow, the headway distribution used was the uniform distribution, where headways were between zero and two times the mean headway.

Speeds were then allocated to each vehicle using the simulations software @RISK, the passing demand was calculated then speeds and headways reallocated. This process was then repeated hundreds of times until a probability distribution of headways were produced.

4. Comparison between Calculated Passing Demands

The differences between the results from using the equations in the PEM for determining passing demand and that predicted using the model developed in Excel were investigated. For this analysis two streams (cars and trucks) were considered, with each stream having a Normal distribution of speeds, and varying standard deviation and differences between the mean speeds of the two streams. These were to analyse over all ranges of γ used in the table presented in the PEM.

The discrepancy between the two models also appeared to be smallest when *Y* is equal to 1 (i.e. when the standard deviations of stream speeds are the same). The simple Excel-based model estimates much greater passing demand when the standard deviation of the truck stream is larger than the standard deviation of the car stream, while Troutbeck's equations give a far lower passing demand in comparison. When the standard deviation of the car stream is larger than the standard deviation of the truck stream, the vehicle-order model gives a lower passing demand, but not to the same extent as the differences that occur with smaller values of *Y*.

Within stream passing demand was also investigated by back-calculating the coefficient in the equation of Wardrop (1952) for car passing car rates:

$$D_{A-A} = 0.564 K_A^{\ 2} s_A \quad \text{(overtakings/km/h)} \tag{11}$$

If there is agreement between the passing demand obtained from equation 11 and the passing demand generated by the Excel-based model, then the coefficient calculated from dividing the passing demand (from the vehicle order model) by the concentration squared and the standard deviation of the speed, should be comparable to the theoretical value of 0.564.

Figure 3 shows the back-calculated values of γ from the mean passing rates for cars passing cars. These should equal 0.564 throughout the range of car speed standard deviations for complete agreement between the vehicle order model and Wardrop's model. It can be seen that the estimate of the coefficient is distinctly less than 0.564 for low standard deviations in speeds, but approaches 0.564 as the standard deviation increases. This comparative underestimation of the passing demand using the Excel-based model is likely to be a function of the headway distribution chosen for the model not allowing for enough vehicle interaction.

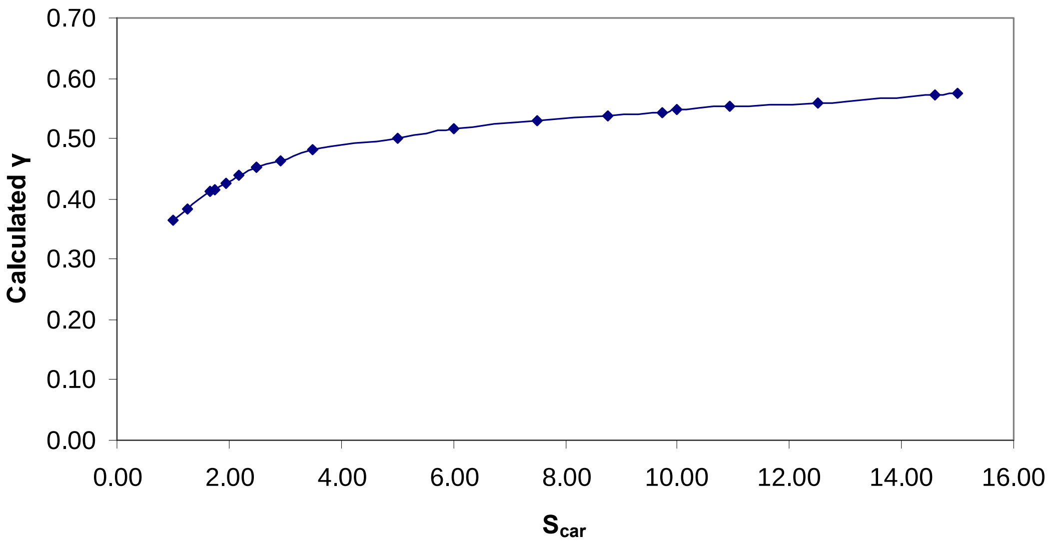

Figure 3: Back-calculated coefficient for car-car passing from model in Excel

Given the large differences in the estimates of passing demand from the Excel model and the PEM equations, it was decided to investigate further the situation where the standard deviation of the stream speed approaches zero.

Three scenarios were investigated using the Excel model, and the resulting passing demands were compared with the estimates obtained from the PEM equations. In these scenarios, the standard deviation of car speeds (Scenario 1), truck speeds (Scenario 2), and both car and truck speeds (Scenario 3) were varied, with all other input parameters remaining constant. The values and distributions used in this analysis are in the following table. For the scenarios with a constant standard deviation of speed, this value was set to 10 km/hr.

Parameter	**Value**
Car Stream Flow Rate, Q_{car}	100 veh/h
Truck Stream Flow Rate, Q_{truck}	20 veh/h
Car Stream Mean Space Speed, $\bar{v}_{car}$	100 km/h
Truck Stream Mean Space Speed, $\bar{v}_{truck}$	90 km/h
Levels of Standard Deviation of Speeds	0, 2.5, 5, 7.5, 10, 12.5 km/h
Speed Distribution Types	Normal
Initial Headway Distribution Type	Uniform (i.e. random headways)

Table 1: Parameters Values for Analysis with Zero Variance in Speed

The results of only the Scenario 1, in which the standard deviation of car speeds was varied, are presented here (Figure 4).

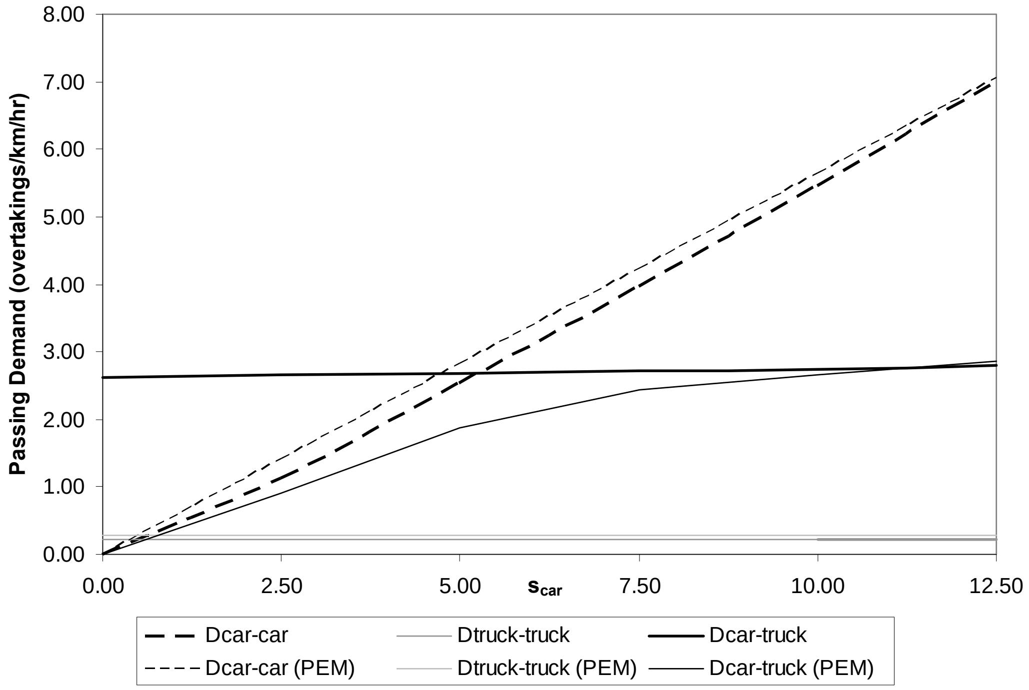

Figure 4: Passing Demand Comparison (0 km/h≤ s_{car} ≤12.5 km/h)

While the car-truck passing demand ($D_{car\text{-}truck}$) would not be expected to reduce much as the standard deviation in car speeds was reduced, due to the 10 km difference in mean speeds, Figure 4 shows the passing demand reducing to zero as the standard deviation of car speeds reduced to zero. Having no demand for cars passing trucks when the mean speeds differ by 10 km/hr indicates that the PEM equations for cars passing trucks does not work well when the standard deviation in car speeds is small.

The key to this problem is the form of the equation for estimating the demand for cars passing trucks:

$$D_{A\text{-}B} = \gamma \times K_A \times K_B \times s_A \qquad \text{(catch-ups/km/h)} \qquad (12)$$

Obviously, as the passing demand must tend to zero as the standard deviation of the stream A speeds approaches zero, unless γ_{ab} has a corresponding multiplicative increase, which it does not and cannot have when s_A is zero. Therefore it can be concluded that PEM equation for passing demand is incorrect when dealing with a low variance in speeds within the streams.

The effect of this is that where a low standard deviation of speed is used in the analysis of passing lane benefits, the current procedure will underestimate passing demand and thus underestimate the benefits. To examine this further, speed data (with low variance) obtained from a vehicle classifier and a proposed passing lane project were used for a comparison of benefit/cost ratios. An analysis using the existing procedure for determining passing demand and the model developed in Excel was then performed. For this particular example, the benefit cost ratio increased by 12 % when using the model developed in Excel in place of the existing procedure.

5. Speed Distributions

Given the above results, it is sensible to ask what standard deviation would we expect in practice, and would it be small enough to give substantial under-estimation of the passing demand when using the PEM simplified procedure? To answer this question traffic counts were analysed from an existing data set obtained by Koorey and Gu (2001). For this analysis, counts at one location along each of three routes were used. These surveys were carried out using automated Metrocount classifiers that collected vehicle speeds, classifications and volumes. Each of the three routes had different terrain and traffic characteristics; the first was a high-volume section of State Highway 1 south of Christchurch on flat terrain, the second was a lower volume section of State Highway 1 in rolling terrain in North Canterbury, and the third was a section of road in very hilly terrain on State Highway 75 between Christchurch and Akaroa.

For each site the speed data were imported into an Excel spreadsheet, vehicles were then classified as either cars or trucks, and then free-flow speeds were used to estimate the passing demand (as required in the PEM). If a vehicle headway was less then 4.0 seconds then the vehicle was deemed to be following.

The distribution-fitting software program BestFit was used to fit probability distributions to the data. BestFit has a range of statistical distributions that it can fit to data using various goodness-of-fit statistics. Distributions were fitted to the speed data for the car stream, the truck stream, and both streams combined.

The results of this fitting of statistical distributions were interesting for two reasons. Firstly, the goodness-of-fit was better for the combined streams than for the individual streams. Secondly, the distribution that was continually fitted to data for both the combined and individual stream was not the Normal distribution but the logistic.

It was surprising that the distributions fitted the combined stream speeds better than for the individual stream speeds, as one reason for having a separate distributions for each stream is that the combined distribution might be bi-modal and might thus not be well-described by a standard uni-modal distribution. Furthermore it was surprising that the fitted distributions were not heavily skewed, particularly for the distributions of speeds in mountainous terrain. The distribution and fit of a combined distribution for the very hilly site (in the uphill direction) is illustrated in Figure 5.

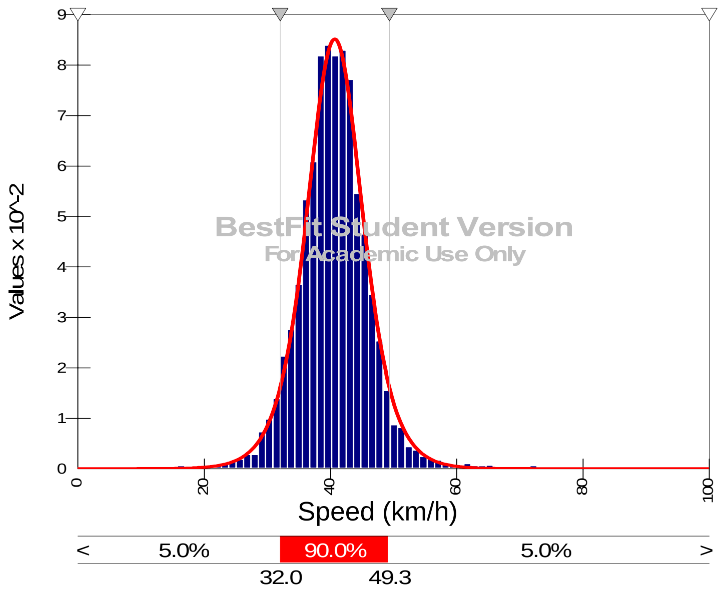

Figure 5: Histogram and Fitted Speed Distribution
(combined free flowing stream in very hilly terrain in uphill direction)

However it is hypothesised that for some sites and analysis periods, combining the streams may not be appropriate. Combining the streams may not be appropriate at sites where there are similar proportions of trucks and cars, with the means of the speed distributions being substantially different. It is unlikely though that this scenario would have a large effect on passing demand calculations for assessment of passing lanes though. This is because it is only likely to occur when total traffic volumes are low, such as late at night when heavy vehicles are still operating but there are very few passenger vehicles. Nevertheless, this issue merits further investigation.

The other interesting aspect of these results was that the Normal distribution was not the best fitting distribution to the data. The best-fit distribution in most cases was the logistic distribution (a bell- shaped distribution, like the Normal distribution), with the log-logistic distribution being fitted in the few cases where the data was skewed. The main reason for the fitting of the logistic distribution is the kurtosis (or "peakiness") of the speed data. The logistic distribution has a kurtosis of 4.2 compared with a kurtosis of 3.0 for the Normal distribution. The data in the samples generally had a kurtosis greater than 4.2 (i.e. closer to the value for the logistic distribution than the Normal distribution.

This indicates that over recent years that the speed distribution of vehicles on the open road may have changed with a large proportion of vehicles now travelling at similar speeds. If this is the case it may affect some of the assumptions made in, and therefore possibly the results of, a range of analyses where the variation in speeds is an important parameter.

6. Passing Demand Using a Single Speed Distribution

The fact that a distribution could be fitted to the combined data for the two streams indicated that there may be scope to simplify the PEM procedure by reducing the data requirements, by having to determine only the mean and standard deviation of the overall stream rather than for two separate streams. To assess the scope, the passing demand was estimated using the distributions for the combined and separate streams.

The datasets for the three above-mentioned locations were used and distributions were fitted to the speed distributions for separate and combined streams. The passing demand was then estimated using the Excel passing demand model. For all three locations there seemed to be only a minimal difference between the total passing demands calculated using a single (combined) stream and using two separate streams (Figure 6). This is perhaps not surprising, given the good fit of the distributions.

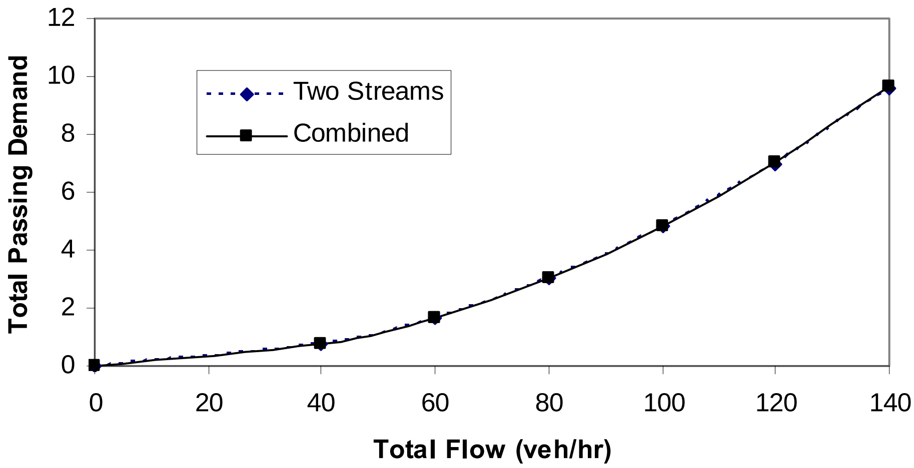

Figure 6: Calculated Passing Demand for Flat Terrain Site

This leads to the possibility of using a single equation, such as the Wardrop (1952) equation, for estimating passing demand from the characteristics of the total traffic stream. If further research confirms the appropriateness of the logistic distribution (rather than Normal distribution) for combined traffic streams, it would be appropriate to develop an equation for estimating passing demand for a single traffic stream with logistic-distributed speeds, equivalent to Wardrop's equation for a single stream with Normal-distributed speeds.

7. Conclusion

It has been shown that in certain circumstances that the equations for determining passing demand used in the PEM underestimate passing demand compared with a computer model based on similar assumptions. This discrepancy is particularly evident when the standard deviation of the speed of the faster stream is small.

This raises doubts about the accuracy and robustness of the equations used in estimating passing demand in the economic evaluation of passing lanes. However through investigation of the speed distributions at three locations in Canterbury and comparison of the total passing demand determined using these distributions, there is a possibility of simplifying the analysis while remedying this problem. This may be through the development of a single equation for determining passing demand using a single speed distribution for all traffic. This would also simplify data requirements, and should be investigated further.

8. References

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