Traffic simulation on two-lane highway downgrades

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Abstract

Traffic operations on long, steep downgrades on high volume primary two-lane highways in Canada often exhibit a lower level of service than on adjoining upgrades or general terrain segments. This is due not only to high traffic flow and increasing percentages of heavy trucks and recreational vehicles in the traffic stream but also to the fact that most downgrades on the Canadian primary highway system have climbing lanes in the opposite direction resulting in long no-passing zones in the downgrade direction.

This paper describes the partial calibration of a downgrade traffic simulation model which, when used in conjunction with TRARR (TRAffic on Rural Roads), ARRB Transport Research Ltd’s two-lane highway traffic simulation model, can provide a basis for estimating the level of service of downgrades. The World Bank micro-transitional model was found to be ‘a good complement’ to TRARR for prediction of traffic flow on downgrades. The ability of TRARR to generate similar traffic characteristics to those observed at the bottom of downgrades demonstrates its robust modelling capability.
This paper presents the partial calibration of a two-lane highway traffic simulation model for downgrade operations. Such a model could be used as the basis for the development of a specific downgrade level of service procedure. It is believed that traffic simulation is an essential tool in the development of such a procedure because conventional mathematical models of traffic flow have proven unsuitable to represent the two-lane traffic flow process (McLean 1989).

The TRARR (TRAffic on Rural Roads) two-lane highway traffic simulation model, developed by the Australian Road Research Board (Hoban et al. 1991), was used to carry out simulation runs for this research study. The TRARR model, however, does not account for the effect of long, steep downgrades on traffic operations. The adaptation of TRARR to simulate downgrade operations involved the selection of a suitable model for the prediction of unimpeded speeds on downgrades.

UNIMPEDED SPEED PREDICTION MODELS ON DOWNGRADES

A review of previous studies showed that at present there are four basic models capable of predicting unimpeded speeds on downgrades:

- regression models;
- St John et al.’s (1970) model, modified by St John and Kobett (1978);
- the Grade Severity Rating System (GSRS) model; and
- the World Bank micro-transitional speed prediction model.

These models, together with their limitations, are explained briefly in the following sections.

Regression models

In these models, the unimpeded speed is directly related to road variables such as grade, curvature, sight distance, auxiliary lanes and barrier line markings. As pointed out by Watanatada et al. (1987), these models have some limitations:

- They can predict unreasonably low values when all the road severity variables take on large values.
- The partial derivative of the predicted speed with respect to each road severity variable is constant. For example, a 1 per cent increment in the rate of downgrade has the same effect on speed on a 1 per cent downgrade (from −1 per cent to −2 per cent) as on a 5 per cent downgrade (from −5 per cent to −6 per cent), which seems unrealistic.
- They are difficult to transfer to areas with different characteristics.

The St John et al. model (1970)

This model was developed by St John, Kobett, Glauz, and Sommerville in 1970 after an analysis of field data of truck speeds on grades throughout the State of California, USA, collected by Webb (1961). The model was based on truck braking capability being proportional to gross vehicle weight. The crawl speeds (V\text{crawl}) on long, steep downgrades were inversely proportional to the grade (GR) as given by the following equation:

\[
V_{\text{crawl}} = \frac{471.43}{(-GR)}
\]

where:

\[
V_{\text{crawl}} = \text{Crawl speed (in km/h)}; \text{ and}
\]

GR = Magnitude of grade (as a %).
St John and Kobett (1978) used the model to provide an estimate for downgrade mean crawl speeds. They noted that mean crawl speeds varied by ± 27 per cent from the values defined by the model and that speeds usually were not affected unless the grade was at least 1600 m long and had a severity of 4 per cent or more.

The St John et al. model also has some limitations:

- Firstly, only truck speeds were considered in the development of the model. While truck speeds are the most severely affected by downgrades, the speeds of other types of vehicles are also required.
- Secondly, the model does not take into account the length of the downgrade, which can have a considerable effect on truck speeds.

Grade Severity Rating System (GSRS) model

The Grade Severity Rating System model for predicting speeds on downgrades was developed by Myers, Ashkenas and Johnson (1980). This model predicts the maximum safe descent speed (the speed that would allow a panic stop at any point on the grade) as a function of truck weight and grade steepness and length for a given maximum brake temperature.

The GSRS model has the following limitations for Canadian conditions:

- Firstly, only semi-trailers with a maximum weight of 36,302 kg were considered in its development. However, in Canada, combination trucks such as B-trains (B-doubles in Australia) have a maximum gross vehicle weight of 62,500 kg.
- Secondly, and more importantly, the model was developed as a mechanistic model rather than a behavioural one; i.e. it was not developed to predict the actual speeds adopted by truck drivers but rather, a maximum safe speed at which trucks should descend the grade.

In spite of the aforementioned problems, this model does give great insight into the effect of the length and the steepness of grade on truck speeds. In fact, in the authors' opinion, if enough data to develop a behavioral model were collected, the equations of this model should be 'a first candidate' for calibration.

The model has no explicit solution, i.e. the speed cannot be expressed explicitly as a function of the grade, its length and the truck weight. Therefore, numerical methods (usually iterative algorithms) have to be used in order to solve this model.

The World Bank speed prediction model

The model used for the present research study was the World Bank micro-transitional speed prediction model. This is one of a set of speed prediction models developed by Watanatada et al. (1987) for the World Bank. The models considered the influence of vertical and horizontal alignment, surface roughness, vehicle performance and desired speeds.

The set of three speed prediction models of the World Bank were developed from analysis of extensive spot speed data collected as part of the Brazil road user cost study (Watanatada et al. 1987). These models are the micro-transitional, the non-transitional, and the aggregate models. Of these, the most detailed and relevant to this study is the micro-transitional model. All three models are based on another model called the steady-state speed prediction model, which will now be briefly explained.

The steady state speed prediction model

The steady-state speed of an unimpeded vehicle of known attributes traversing a homogeneous road section of known characteristics, located in a given socioeconomic and traffic environment, was defined as the speed the vehicle would eventually attain and maintain if the homogeneous road section were infinitely long. A 'homogeneous section' was defined as 'a stretch of road over which the characteristics of interest do not change appreciably'.

The steady-state speed model takes a limiting approach in which, instead of directly associating the steady-state speed with the speed influencing parameters of the homogeneous section, a set of five steady-state 'limiting' or 'constraining' speeds with the speed influencing parameters is considered first of all. The model relates the vehicle steady-state speed to a minimum of five constraining speeds which are treated as random variables with a Gumbel distribution, which is a probabilistic limiting speed model. It is described by the following equation:
where:

\[ \sigma^2 = \text{Variance associated with unmeasured vehicle, road, and speed measurement characteristics;} \]

\[ \beta = \text{A constant parameter for each vehicle class;} \]

\[ V_{SS} = \text{The attained steady state speed;} \]

\[ V_{DRIVE} = \text{The speed limited by gradient and driving power;} \]

\[ V_{BRAKE} = \text{The speed limited by gradient and braking power;} \]

\[ V_{CURVE} = \text{The speed limited by curvature;} \]

\[ V_{ROUGH} = \text{The speed limited by roughness; and} \]

\[ V_{DESIR} = \text{The desired speed in the absence of road severity factors.} \]

The maximum driving speed, \( V_{DRIVE} \), was determined from the vehicle force balance equation according to an estimated parameter, \( HP_{DRIVE} \), representing the used driving power. The optimal speed at which a vehicle can negotiate a horizontal curve, \( V_{CURVE} \), was determined from the curve design equation. The roughness-limited speed constraint, \( V_{ROUGH} \), was defined as a function of pavement roughness parameters. The desired speed, \( V_{DESIR} \), was defined as the speed at which drivers travel when they are not constrained by the road features explicitly included in eqn (2). This speed constraint implicitly contains behavioral responses to such factors as safety, speed limits, and driver perception of enforcement.

The maximum braking speed was also determined from force-balance considerations according to an estimated parameter, \( HP_{BRAKE} \), which represents the maximum used braking power. The following cubic equation had to be solved:

\[ \frac{1}{2}pC_dARV^3 - mg(CR + GR)V - 736 HP_{BRAKE} = 0 \]  

where:

\[ \rho = \text{Mass density of air (in kg/m}^3); \]

\[ C_d = \text{Dimensionless aerodynamic drag coefficient of the vehicle;} \]

\[ AR = \text{Projected frontal area of the vehicle (in m}^2); \]

\[ m = \text{Vehicle mass (in kg);} \]

\[ g = \text{Acceleration of gravity (in m/s}^2); \]

\[ CR = \text{Dimensionless coefficient of rolling resistance;} \]

\[ GR = \text{Road gradient, expressed as a fraction; and} \]

\[ HP_{BRAKE} = \text{Maximum used braking power (in hp)} \]

Equation (3) applies to downgrades in which \((CR + GR) < 0\). Watanatada et al. (1987) argued that, since the braking speed constraint is binding only on steep negative grades where the steady-state speeds are relatively low, the air resistance term could be neglected without causing much error in the solution. Thus eqn (3) was simplified to the following equation:

\[ V_{BRAKE} = \begin{cases} - \frac{736 HP_{BRAKE}}{mg(CR + GR)} & \text{if } (GR + CR) < 0 \\ 0 & \text{if } (GR + CR) \geq 0 \end{cases} \]  

As was mentioned before, the micro-transitional speed prediction model is based on the steady-state model just described. The micro-transitional model predicts the speeds of different vehicle types at closely spaced points (usually 100 m apart or at the beginnings and ends of curves or points where the grade changes). The distances between these points are called 'simulation intervals'.

The model proceeds in two phases. The first phase consists of a backward recursion in which the maximum allowable entry speed for a simulation interval is determined. In the second phase, the forward recursion, the actual unimpeded speed profile, is simulated. Power usage is defined so that the speed is as high as possible, subject to the constraint of the maximum speed profile obtained in the first phase. The details of this model are explained in Watanatada et al. (1987) whereas some minor changes to its logic, implemented for this research, are explained in Archilla (1992).
CALIBRATION OF THE DOWNGRADE SPEED PREDICTION MODEL

In order to calibrate the micro-transitional speed prediction model for Canadian conditions, the data collected on two steep, long downgrades (the Great Divide and Ottertail Hill downgrades) and on level sections of the Trans-Canada Highway in Yoho National Park in the province of British Columbia, Canada, were used. The two downgrades are single-lane with 100 per cent no passing zones.

In order to test the World Bank model, a program in QuickBasic was developed. Ideally, the calibration of the parameters $\beta$ and $\sigma$ should be done using a non-linear least-squares regression analysis between observed speeds and speed constrained terms, whereas the other parameters could be calibrated using a simplified procedure described in Watanatada et al. (1987). Nevertheless, the speeds predicted with the Brazil values for $\beta$ and $\sigma$ did not agree very well with the observed data, and therefore it was felt that a modification of these parameters was necessary so that the predicted values approximated as much as possible to the observed unimpeded speeds on the Great Divide - top and bottom of the grade, and on the Ottertail Hill - bottom of the grade and on level sections. Because of the limited number of locations studied, a major premise of this calibration phase was that as few parameters as possible would be changed. This meant that whenever possible the original model parameters used by Watanatada et al. (1987) were used.

The first step of the calibration was to select some vehicle performance parameters such as drag coefficient, vehicle frontal area and vehicle mass that were representative of North American conditions. It should be noted that this was not an easy task not only because the types of vehicles on a highway are so varied but also because different makes of the same vehicle usually have different performance parameters. The parameter values for this study (see Table 1) were compiled from Werner (1987), St John and Kobett (1978), Watanatada et al. (1987), Elkins and Semrau (1988), and Consumer Reports (1992).

In the second stage, an attempt was made to modify the parameters $\beta$, HPRIDE, HPBRAKE, $\sigma$ and VDESIR for each vehicle type, to obtain a good approximation to the observed values in the three downgrade locations and in the level sections.

However, it soon became apparent that this was not possible because the predicted speeds could never be approximated to the observed speeds at the top and at the bottom of the Great Divide downgrade simultaneously. A re-examination of the model showed that the problem is in eqn (4) because, for example, when the effective gradient (CR+GR) is doubled, VBRAKE is halved. However, the differences between the observed speeds on a 4.45 per cent local downgrade (at the top of the Great Divide) and a 6.51 per cent local downgrade (at the bottom of the Great Divide) were very small (Archilla and Morall 1994). Although the micro-transitional model attenuates the difference predicted by the steady-state model, this is not enough to get the predicted speeds even closer to the observed speeds.

Equation (4) was modified to predict passenger car and recreational vehicle (RV) speeds on downgrades as follows:

$$V_{\text{BRAKE}} = \begin{cases} 736 \text{ HPBRAKE} & \text{if} (GR+CR) < 0 \\ 0 & \text{if} (GR+CR) \geq 0 \end{cases}$$

Table 1

<table>
<thead>
<tr>
<th>Vehicle type</th>
<th>Drag coefficient</th>
<th>Frontal area (m²)</th>
<th>Vehicle mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passenger Cars</td>
<td>0.40</td>
<td>2.4</td>
<td>1450</td>
</tr>
<tr>
<td>Recreational Vehicles</td>
<td>0.55</td>
<td>3.0</td>
<td>3170</td>
</tr>
<tr>
<td>Buses</td>
<td>0.65</td>
<td>6.3</td>
<td>17200</td>
</tr>
<tr>
<td>Single-Unit Trucks</td>
<td>0.70</td>
<td>4.5</td>
<td>8300</td>
</tr>
<tr>
<td>Semi-trailer Trucks</td>
<td>0.62</td>
<td>8.0</td>
<td>30000</td>
</tr>
<tr>
<td>Combination Trucks</td>
<td>0.67</td>
<td>8.0</td>
<td>35000</td>
</tr>
</tbody>
</table>
Table 2

Calibrated parameters for passenger cars and recreational vehicles

<table>
<thead>
<tr>
<th>Vehicle type</th>
<th>$\beta$</th>
<th>HPDRIVE</th>
<th>HPBRAKE</th>
<th>$\sigma$</th>
<th>VDESIR</th>
<th>$\delta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passenger Cars</td>
<td>0.14</td>
<td>50.0</td>
<td>290.0</td>
<td>0.060</td>
<td>100.1</td>
<td>0.20</td>
</tr>
<tr>
<td>Recreational Vehicles</td>
<td>0.12</td>
<td>73.3</td>
<td>740.0</td>
<td>0.060</td>
<td>97.2</td>
<td>0.10</td>
</tr>
</tbody>
</table>

where:

$j$ = Simulation interval; and

$GR_j$ = Road gradient expressed as a fraction in interval $j$.

where $\delta (0 < \delta < 1)$ is a parameter used to reduce the sensitivity of speed to the effective gradient.

The parameter values in Table 2 were obtained by trial and error. Figure 1 shows the predicted speeds vs the observed speeds for passenger cars and RVs. As can be seen, the predictions are acceptable and it is expected that the speed profile produced with these parameters would be very close to the real speed profile on the downgrade studied. However, because these parameters are based on observations at a very small number of sites, their values are not reliable and should not be used for downgrades with different characteristics.

It is important to point out that eqn (5) has been chosen only for simplicity and it is the authors' opinion that in future research, a more elaborate formula will be needed to represent these speeds. In particular, it is believed that it is the combination of the local downgrade with the total length downgrade and average downgrade, and not the local downgrade alone, that affects these vehicle speeds.

For heavy trucks, the selection of a model of $VBRAKE_j$ was also difficult. At first, the Grade Severity Rating System (GSRS) developed by Johnson et al. (1982) was considered. One potential limitation of the GSRS is that in its development only five-axle semi-trailers with a maximum weight of 36,320 kg were considered. While this is representative of US conditions, the maximum weights and vehicle configurations in Canada are quite different (the weight limit for combination trucks is 62,500 kg). Therefore, it is expected that some calibration with more extensive data would be needed before the model can be used to predict downgrade speeds accurately.

Given the above limitations, attention was given to a model of the form of that used by St John and Kobett (1978). The equation that represents this model, namely eqn (1), has the same form as eqn (4), and both are a function of the inverse of the grade. It is noted that eqn (4) considers only the local downgrade whereas the St John model eqn (1) considers the average rate of downgrade for the whole section.

The expression finally used to represent $VBRAKE_j$ was eqn (4), but with the grade parameter representing the average rate of downgrade for the whole downgrade instead of the local downgrade.

The speeds of single-unit trucks and buses are much more severely affected by downgrades than those of passenger cars and RVs but less so than those of heavy trucks. As these vehicle types represented a small percentage of the total traffic volume, it was...
Table 3
Calibrated parameters for buses and trucks

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>$\beta$</th>
<th>HPDRIVE</th>
<th>HPBRAKE</th>
<th>$\sigma$</th>
<th>VDESIR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buses</td>
<td>0.262</td>
<td>220.0</td>
<td>241.4</td>
<td>0.160</td>
<td>101.5</td>
</tr>
<tr>
<td>Single-Unit Trucks</td>
<td>0.149</td>
<td>160.0</td>
<td>102.5</td>
<td>0.040</td>
<td>97.9</td>
</tr>
<tr>
<td>Semi-trailer Trucks</td>
<td>0.210</td>
<td>425.0</td>
<td>318.9</td>
<td>0.269</td>
<td>101.5</td>
</tr>
<tr>
<td>Combination Trucks</td>
<td>0.251</td>
<td>450.0</td>
<td>291.9</td>
<td>0.289</td>
<td>101.5</td>
</tr>
</tbody>
</table>

decided to represent $V_{\text{BRAKE}}^j$ also by eqn (4), with the same interpretation for $GR_j$ as for heavy trucks.

Again, by trial and error, the parameters shown in Table 3 were found to give the best speed estimates. Figure 2 shows how well the predicted speeds compared to the observed speeds.

Figure 3 shows the variation in the predicted speeds with grade for passenger cars, RVs, semi-trailers, and combination trucks. While the speed curves are as expected, the sharp change in curvature for passenger cars and RVs at an approximately 2.3 per cent downgrade is noted. This is, of course, a direct consequence of the chosen expression for $V_{\text{BRAKE}}^j$ and it shows that a better expression has yet to be found.

INCLUSION OF THE WORLD BANK MICRO-TRANSITIONAL MODEL INTO TRARR

TRARR makes use of road speed indices to account for the effects of curves on unimpeded speeds. As this research project was not intended to make any changes to the TRARR logic, it was decided to use the road speed indices to account for the effects of downgrades.

In the TRARR program, each speed index corresponds to a set of speed multipliers for each vehicle group. These speed multipliers are in a 24 x 4 table (24 speed indices for 4 vehicle groups) in a data statement within the TRARR program.

![Figure 2](image-url)

Figure 2
Calibration results of the World Bank speed prediction model for buses, single unit trucks, semi-trailers, and combination trucks.

![Figure 3](image-url)

Figure 3
Speed versus grade relationship predicted by the modified World Bank speed prediction model for passenger cars, recreational vehicles, semi-trailers and combination trucks.
The inclusion of the World Bank model into TRARR was then achieved as follows. Firstly, TRARR was modified to read a $300 \times 6$ table of speed multipliers so that smaller speed changes could be taken into account. Also, with this bigger table more varied situations could be considered. To illustrate this, consider the following hypothetical situation: the mean desired speed of 'vehicle group 1' is 100 km/h and the mean desired speed of 'vehicle group 2' is 90 km/h. Further, it was assumed that the mean unimpeded speed of group 1 vehicles was 80 km/h according to the micro-transitional model, implying a speed multiplier equal to 0.8. However, this does not imply that these two sections correspond to the same speed index because the mean unimpeded speed of group 2 vehicles is 60 km/h for the first segment and 80 km/h for the second (implying speed multipliers of 0.767 and 0.89 respectively). Thus, there are two speed indices, one of which corresponds to the speed multipliers 0.80 and 0.67 for vehicle groups 1 and 2 respectively, and the other which corresponds to the speed multipliers 0.80 and 0.89. It is noted that, because of the different vehicle performances on grades for the different vehicle groups, more speed indices are required than are normally used in the TRARR program.

Finally, it is noted that two vehicle groups were added (increasing the number from 4 to 6). The micro-transitional model was run and its results were read by another program, created by the authors in QuickBasic, which found the ratio between the speed on the grade and the desired speed for each vehicle type and for each simulation interval; then a speed index was assigned to each combination of speed multipliers for the six vehicle categories.

**SIMULATION OF THE ENTRY PROCESS**

**Traffic composition**

To determine how well the model simulated the entry process, the data collected at the top of the Great Divide downgrade was used. Since there was great variation in speed on the downgrade between the different vehicle types, it was very important that the traffic composition for the simulated traffic should be as close as possible to that of the observed traffic. However, TRARR uses the traffic composition data specified in the traffic file to generate vehicle types by means of random sampling.

Therefore, a trial and error process was carried out to obtain output traffic composition that approximately matched the input traffic composition. Table 4 shows the observed and simulated vehicle type percentages and their differences. As can be seen, very close matches were found.

**Observed vs simulated traffic characteristics**

Although there are some headway and platoon size distributions that are suitable for representing the entry process to a section of a two-lane highway, there is, as yet, no method to estimate the values of their parameters as a function of the traffic and

<table>
<thead>
<tr>
<th>Volume (veh/h)</th>
<th>Vehicle type</th>
<th>P.C.</th>
<th>R.V.</th>
<th>Bus</th>
<th>S.U.</th>
<th>S.T.</th>
<th>C.</th>
</tr>
</thead>
<tbody>
<tr>
<td>319</td>
<td>Obs. (%)</td>
<td>82.89</td>
<td>11.72</td>
<td>1.00</td>
<td>1.19</td>
<td>2.07</td>
<td>1.13</td>
</tr>
<tr>
<td></td>
<td>Sim. (%)</td>
<td>82.82</td>
<td>11.76</td>
<td>0.93</td>
<td>1.24</td>
<td>2.01</td>
<td>1.24</td>
</tr>
<tr>
<td></td>
<td>Diff. (%)</td>
<td>0.07</td>
<td>-0.04</td>
<td>0.07</td>
<td>-0.05</td>
<td>0.06</td>
<td>-0.11</td>
</tr>
<tr>
<td>407</td>
<td>Obs. (%)</td>
<td>87.73</td>
<td>8.57</td>
<td>0.55</td>
<td>0.71</td>
<td>1.60</td>
<td>0.84</td>
</tr>
<tr>
<td></td>
<td>Sim. (%)</td>
<td>87.62</td>
<td>8.54</td>
<td>0.62</td>
<td>0.74</td>
<td>1.61</td>
<td>0.87</td>
</tr>
<tr>
<td></td>
<td>Diff. (%)</td>
<td>0.11</td>
<td>0.03</td>
<td>-0.07</td>
<td>-0.03</td>
<td>-0.01</td>
<td>-0.03</td>
</tr>
<tr>
<td>540</td>
<td>Obs. (%)</td>
<td>85.14</td>
<td>8.84</td>
<td>0.40</td>
<td>0.80</td>
<td>0.80</td>
<td>4.02</td>
</tr>
<tr>
<td></td>
<td>Sim. (%)</td>
<td>85.14</td>
<td>8.79</td>
<td>0.47</td>
<td>0.84</td>
<td>0.84</td>
<td>3.93</td>
</tr>
<tr>
<td></td>
<td>Diff. (%)</td>
<td>0.00</td>
<td>0.05</td>
<td>-0.07</td>
<td>-0.04</td>
<td>-0.04</td>
<td>0.09</td>
</tr>
</tbody>
</table>

roadway characteristics (Archilla 1992). Since TRARR uses the Borel-Tanner distribution, combined with the negative exponential distribution for interplatoon headways and warm-up zones to generate traffic, attention was given to the comparison of the simulated and observed traffic characteristics at the entry to the simulated section.

When the first simulation runs were done, there was great variation in the simulated and observed traffic characteristics when compared. In all cases, the percentage of vehicles following (percent following) at headways less than 5 seconds (percent following) was greatly underestimated, with the differences ranging from 16 per cent to 19 per cent. Speeds, on the other hand, were overestimated; especially for the 540 veh/h volume, for which a difference of 8.8 km/h was found. Finally, great differences were also found between the observed and predicted speed standard deviations. They were underestimated in all cases and the percentage difference with respect to the observed standard deviations ranged from 28 per cent to 38 per cent.

As TRARR had already been calibrated successfully for Alberta (Canada) highways in level sections with passing opportunities, it was thought that the best solution to the above problem would be to add a realistic length of highway to the simulated section before the entry point (referred to as a 'warm-up' zone). Several simulations were carried out, in which the length of the warm-up zone was increased each time - up to a maximum length of 7 km. It was expected that, as the length increased, a point would have been reached where the entry process would have become independent of the added length. However, this was not the case. Instead of reaching an equilibrium point, the percent following kept increasing to much higher levels than the observed values whereas the simulated speeds kept decreasing to lower levels than the observed speeds.

In the study section there was a 1.2 km right-turn lane into a lodge and a gas station located 1.3 km upstream of the entry point, that was being used by many drivers as a passing lane. Unfortunately this is only based on the authors' observations while they were traversing this section of highway and no formal measurements were carried out. Thus, the proportion of people using this section as a passing lane, or the length of the section actually used as a passing lane, was not known. Simulation runs were also carried out considering the total length of the right-turning lane as a passing lane. In this case, the results were reversed; i.e. percent following was underestimated and the speeds were slightly overestimated. The best approximation was found when 67 per cent (800 m) of the right-turning lane was coded as a passing lane. Table 5 shows the comparison of the observed and simulated values. As can be observed, the percent following and the speed differences are quite reasonable and the errors produced are well within the limits of the errors of the input data. However, the differences in speed standard deviations are very prominent.

<table>
<thead>
<tr>
<th>Volume (veh/h)</th>
<th>Traffic characteristics</th>
<th>Observed</th>
<th>Simulated</th>
<th>Δ</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>319</td>
<td>Speed (km/h)</td>
<td>89.5</td>
<td>88.7</td>
<td>0.8</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>σ (km/h)</td>
<td>14.2</td>
<td>11.9</td>
<td>2.3</td>
<td>16.2</td>
</tr>
<tr>
<td></td>
<td>% following</td>
<td>51.2</td>
<td>48.5</td>
<td>2.7</td>
<td>5.3</td>
</tr>
<tr>
<td>407</td>
<td>Speed (km/h)</td>
<td>91.2</td>
<td>88.8</td>
<td>2.4</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td>σ (km/h)</td>
<td>14.1</td>
<td>10.9</td>
<td>3.2</td>
<td>22.7</td>
</tr>
<tr>
<td></td>
<td>% following</td>
<td>56.9</td>
<td>54.5</td>
<td>2.4</td>
<td>4.2</td>
</tr>
<tr>
<td>540</td>
<td>Speed (km/h)</td>
<td>80.9</td>
<td>81.2</td>
<td>-0.3</td>
<td>-0.4</td>
</tr>
<tr>
<td></td>
<td>σ (km/h)</td>
<td>20.1</td>
<td>14.8</td>
<td>5.3</td>
<td>26.4</td>
</tr>
<tr>
<td></td>
<td>% following</td>
<td>66.7</td>
<td>66.4</td>
<td>0.3</td>
<td>0.4</td>
</tr>
</tbody>
</table>
Perhaps, more important than the comparison of the observed vs simulated values for each individual volume of vehicles per hour, is the observation of how well the model behaves when certain traffic variables are changed. In this respect, TRARR coupled with the World Bank micro-transitional model has performed quite well. For example, in spite of the increase in volume from 319 to 407 veh/h, the observed speed did not decrease because the 407 veh/h volume had a lower percentage of heavy vehicles. As can be seen in Table 5, this behavior is modeled very closely. Further, there is a 10 km/h drop in the observed speed for the 540 veh/h flow due to an increase in the percentage of combination vehicles. This behavior is also very well modeled. At the same time the simulated percent following shows the same trends as the observed ones.

It is noted that percent following output provides just one point of the cumulative headway distribution and that to judge how well the model is simulating the entry process, it may be more useful to compare the observed and simulated headway distributions. This is shown in Figure 4. As can be seen, the simulated distribution fits very closely to the observed distribution.

With respect to the question of how long the added section of highway should be, it was found that a length of 5 to 6 km was acceptable. This is in agreement with the studies of Stock (1976) and Hoban (1980), which suggest that a warm-up zone of at least 6 km is required to obtain equilibrium operations. Nevertheless, for this study, this finding should be used cautiously because the results are strongly dependent on the assumption that the right-turning lane will be used as a passing lane.

In summary, it can be concluded that the entry process generated by the TRARR model can be very inaccurate, depending on the traffic composition and the roadway characteristics upstream of the entry section. This observation could also be true for other simulation programs which generate the entry process by means of headway or platoon size distributions whose parameters depend only on traffic volume.

An alternative method for generating traffic is to add a realistic length of highway in advance of the section to be observed. Although, the inclusion of such warm-up zones significantly increases the simulation time, it is necessary in order to obtain a more reliable entry process.

**THE EXIT PROCESS**

Table 6 shows the comparison of the observed and simulated traffic characteristics for the bottom of the Great Divide.

The standard deviation of the speed was again greatly underestimated. Similar differences in $\sigma$ have been found by Wong (1987) in level sections. As in any stochastic simulation, the results would never be perfect; however, for this study, there is an additional reason why the differences are so high. To assign the unimpeded speed on a level section to a given vehicle, TRARR samples from a normal distribution with the mean and the standard deviation in level terrain corresponding to the given vehicle type. Then, when this vehicle enters the downgrade, its speed is multiplied by a road speed multiplier that is generally a number less than one to account for the reduction in speed on the downgrade. The effect of this is a reduction in the standard deviation in the downgrade with respect to the standard deviation on level terrain. However, the data shows that the standard deviation of speed is much higher on the downgrade sections than on
Traffic on two-lane downgrades

Table 6
TRARR Calibration (Great Divide - bottom of the grade)

<table>
<thead>
<tr>
<th>Volume (\text{veh/h})</th>
<th>Traffic Characteristics</th>
<th>Observed</th>
<th>Simulated</th>
<th>(\Delta)</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>277</td>
<td>Speed (km/h)</td>
<td>82.7</td>
<td>78.9</td>
<td>3.8</td>
<td>4.6</td>
</tr>
<tr>
<td></td>
<td>(\sigma) (km/h)</td>
<td>13.1</td>
<td>12.5</td>
<td>0.6</td>
<td>4.6</td>
</tr>
<tr>
<td></td>
<td>% following</td>
<td>54.5</td>
<td>55.1</td>
<td>-0.6</td>
<td>-1.1</td>
</tr>
<tr>
<td>309</td>
<td>Speed (km/h)</td>
<td>82.2</td>
<td>76.2</td>
<td>6.0</td>
<td>7.3</td>
</tr>
<tr>
<td></td>
<td>(\sigma) (km/h)</td>
<td>16.1</td>
<td>13.1</td>
<td>3.0</td>
<td>18.6</td>
</tr>
<tr>
<td></td>
<td>% following</td>
<td>59.6</td>
<td>61.2</td>
<td>-1.6</td>
<td>-2.7</td>
</tr>
<tr>
<td>402</td>
<td>Speed (km/h)</td>
<td>83.5</td>
<td>76.1</td>
<td>7.4</td>
<td>8.9</td>
</tr>
<tr>
<td></td>
<td>(\sigma) (km/h)</td>
<td>13.2</td>
<td>11.6</td>
<td>1.6</td>
<td>12.1</td>
</tr>
<tr>
<td></td>
<td>% following</td>
<td>66.0</td>
<td>69.0</td>
<td>-3.0</td>
<td>4.6</td>
</tr>
</tbody>
</table>

level terrain, even though the average speed is reduced.

In order to account for the increase in the standard deviation of the speeds on the downgrades, the following experiment was carried out. Firstly, the speed and standard deviation for each vehicle type in the downgrade was divided by the corresponding speed and standard deviation on level terrain to obtain speed and standard deviation multipliers. Then, a linear regression was carried out considering only those speed multipliers that were less than one, because there were not enough data points for a regression with the speed multipliers greater than one. It should be noted that single-unit trucks and buses were not included because of the small sample sizes. The result of regression was:

\[
f \sigma = 7.06 - 6.06 f_v \quad (R^2 = 0.73)
\]  

(6)

where:

\[f \sigma\] = A multiplier for \(\sigma\) that accounts for the increase in the downgrade, and

\[f_v\] = The speed multiplier.

Then, instead of directly multiplying by the speed multiplier to obtain the speed in the downgrade, TRARR was modified to calculate this speed as follows:

\[V_d = f_v \cdot V_{SS} + f \sigma (V_L - V_{SS})\]  

(7)

As can also be seen in Tables 5 and 6, the speed was generally underestimated. Nevertheless, the differences were well within the errors in the input data. It is worth noting that for this study, there are several factors that could have contributed to make these differences greater. Firstly, the unimpeded speed estimates on the downgrade sections were derived from measurements with high levels of platooning. This would have probably produced an underestimation of the unimpeded speeds. Secondly, the speed indices were based on a model
The speed, percent time spent following, and operational delay to the entry conditions should be investigated.

• Traffic on two-lane downgrades not properly calibrated. Thirdly, high proportions of shoulder overtakings and illegal passes were observed. Fourthly, the observed proportion of motorcycles was modelled as if it was for passenger cars.

CONCLUSIONS

The World Bank micro-transitional speed prediction model was found to be ‘a good complement’ to TRARR for prediction of traffic flow on downgrades. The ability of TRARR to generate similar traffic characteristics to those observed at the bottom of the downgrades demonstrates its robust modelling. The errors produced by the model are well within the limits of the input data. However, the problem of underestimation of speed standard deviations still has to be solved. Although an attempt to account for the increase in standard deviation of speed on downgrades was made, the results were not satisfactory.

This paper has shown that more research is needed for the development of a methodology for level of service calculation on downgrades. Development of such a model should consider the following areas:

(1) Development of a speed prediction model on downgrades

• A data collection and analysis program to determine an appropriate expression for the limiting speed on downgrades in the World Bank model should be carried out. This program should concentrate on the relationship between the unimpeded speed of each vehicle type and grade. The effects of the local rate of downgrade, the average rate of downgrades, and the length of the downgrade should be identified.

• Truck weight data should also be collected at the same time as speeds are measured, so that the effect of weight on truck speed can be accurately determined.

• An analysis of the feasibility of the calibration for heavy trucks found on Canadian highways of the Grade Severity Rating System equations as a speed prediction model on downgrades should be carried out.

(2) TRARR - modifications and validation

• TRARR should be modified so that the calculation of the road speed indices is done internally using the World Bank model.

• The model should also account for the variation in the standard deviation of the speed in sections with different characteristics.

• The use of actual sections of highway as warm-up zones should be considered. In particular, the road conditions and traffic behaviour along the warm-up zone should be carefully monitored.

• The sensitivity of speed, percent time spent following, and operational delay to the entry conditions should be investigated.

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REFERENCES


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