



## **ASSESSING THE COST OF ROAD GEOMETRIC IMPROVEMENTS FOR LONGER VEHICLES**

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### **ABSTRACT**

The transport industry in New Zealand is seeking a significant improvement in productivity through an increase in the maximum allowable heavy vehicle weights and lengths. As part of a major investigation into the feasibility of such increases the costs associated with widening various sectors of the State highway network to accommodate longer vehicles has been determined.

To determine the widening costs a novel evaluation tool has been developed. This tool uses as input high-speed and low-speed tracking for the vehicle options, standardised curve and roundabout widening costs for different terrain and land use options, and a range of curve and roundabout geometries.

Tracking was determined using multi-body simulation models for the low and high-speed manoeuvres. Propriety vehicle tracking software was used as a cross-check for the low-speed manoeuvres. Road trials using an instrumented 25m 62 tonne B-train were undertaken at highway speeds on a section of the State highway and at closed-off intersections and roundabouts in order to validate the model. A very good match between measured and simulated wheel tracks was found.

An inventory of the current geometry (curves and roundabouts) on the route sectors under consideration was developed. By applying the evaluation tool, which incorporates tracking requirements and cost data to this inventory, the total cost of the necessary road widening was estimated.

## 1.0 INTRODUCTION

Heavy vehicle related research in New Zealand (NZ) over the last twenty years has focused primarily on vehicle performance (alternative fuels, emissions, load securing, brake performance, handling and stability) and the effects of Heavy Vehicles (HV) on pavement life, including HV suspension evaluation for road friendliness. In the last eight years the role of the driver in relation to driver awareness, fatigue and driver modelling has increasingly being researched (White and Thakur, 1995; Charlton, 1997). This earlier research has led to a major research programme looking at the whole and individual components of driver/vehicle/road interaction, with the aim of improving the efficiency and safety of road transport in NZ. This research programme makes use of instrumented vehicle tests, driver monitoring, driver simulator tests and accelerated pavement tests to gather data for model development and validation.

New Zealand's heavy vehicle limits were last reviewed in 1988, at which time the Gross Combination Mass (GCM) and Overall Length (OAL) of truck full-trailer and B-Train (tractor, semi-trailer, semi-trailer) combinations were increased to 44 tonnes and 20 metres respectively. Tractor semi-trailer combinations were permitted a GCM of 39 tonnes and OAL of 17m. A-Trains (tractor, semi-trailer, full-trailer) were restricted to the old GCM of 39 tonnes and an OAL of 19 metres due to their poorer dynamic stability. A-trains have subsequently been permitted a GCM of 44 tonnes if strict performance measures are met and each combination certified as meeting these requirements.

In 1992 and 1996 studies instigated by the State Highway (SH) network provider – Transit NZ – and reported on at the 5<sup>th</sup> symposia (Sleath and Wanty, 1998) indicated that the costs involved in upgrading the geometrics and bridges on the SH network to allow heavier and longer vehicles outweighed the potential benefits. Pressure from exporters, the transport industry and a review of the methodology used to determine the geometric and bridge costs in the earlier studies led to a new study being commissioned in 1998. One component of this new study was to determine the cost of upgrading the geometrics (curves and roundabouts) of the SH network to allow heavier and longer combination vehicles. Figure 1 details the structure of this project and how it fits into the rest of the Transit NZ Heavy Vehicle Limits (HVL) project. The principal aims of this paper are to outline:

1. The processes and steps taken to determine the costs relating to the required geometric upgrading of the SH network or parts of it to accommodate heavier and longer vehicles.
2. Where the work carried out has synergies to ongoing research into driver/vehicle/road interaction being undertaken by TERNZ Ltd.

## 2.0 METHODOLOGY

Previous studies in 1992 and 1996 (Sleath and Wanty, 1998) used the amount of low speed offtracking, (low speed offtracking being defined as that occurring at creep speed (less than

10 km/h)) on a number of idealised curves of differing radii to determine the required increase in road width for highway curves. In a review of these earlier studies it was proposed that using low speed offtracking to determine road widening requirements would over-estimate the required increase in road space on all but the sharpest (nominal radius of less than 50 m) highway curves.

The amount of Low Speed Offtracking (LSO) on level ground is primarily dependent on the wheelbase lengths of the individual units, the number of hitches and the hitch offset distances. At low speeds the slip angles and side forces generated at the tyre road interface in multi-axle groups can be ignored without significant error. Steady state LSO is not normally achieved unless the curve deflection angle is  $270^\circ$  or greater (Woodroffe, Smith et al., 1985).

At low speeds greater than 8 km/h the offtracking will be less than the creep speed assumption but still inboard of the steer axle path. For a given curve geometry as speed is increased there will be a transition from inboard to outboard offtracking, see Figure 1. The term High Speed Offtracking (HSO) is defined as the offtracking distance between the steer axle and rear axis paths at speeds greater than 8 km/h and may be either inboard or outboard offtracking. The level of lateral acceleration and the sum of the cornering stiffnesses at each axle group are the primary determinants of the speed at which the transition from inboard to outboard offtracking occurs for a given combination type and curve radius. Measures that reduce low speed offtracking will cause the transition from inboard offtracking to outboard offtracking to occur at lower levels of lateral acceleration (Segal, 1988).

For the geometric evaluation of the SH network reported in this paper, the amount of offtracking occurring at speeds appropriate for the given curve geometry was determined by computer simulation. The computer models used in this analysis and the assumptions in determining the representative curves and speeds are described in sections 2.1 and 2.2 below.

## **2.1 Computer Simulation Models**

Two simulation models were developed using AutoSim. The first model represented a six axle tractor semi trailer and the second a nine axle B-Train. AutoSim is an equation generator for models of mechanical systems. It generates the computer source code for solving a set of nonlinear symbolic equations in languages such as Fortran or C. AutoSim was developed for building large, complicated vehicle dynamics simulation programs at the University of Michigan's Transport Research Institute, (UMTRI) and is sold commercially by Mechanical Simulation Corporation.

With AutoSim a mechanical system is described as a series of rigid bodies, joints, springs, applied forces and moments. The description of the system is used by AutoSim to generate the equations of motion in the chosen computer language. How well the model simulates the actual mechanical system depends on the assumptions made in describing the system.

The ability of AutoSim to generate accurate solutions to the equations of motion has been well documented, (Sayers, 1989; Sayers and Riley, 1996). The assumptions used in describing the tractor semi trailer system followed the outline given in (Sayers and Riley, 1996), including non-linear spring and tyre routines, see also (Fancher, Ervin et al., 1980). An implementation of the driver model described by (MacAdam, 1981) was used so that the simulations could be run in closed loop mode, that is, the model could be steered to follow a specified x-y path with minimal tracking error.

A field trial with a 26.5 m 62 tonne B-Train was conducted to validate the tracking predictions of the B-Train model on high and low speed curves, including a typical roundabout and Tee intersection. The path taken by the steer axle and rear axis of the rear semi trailer as well as lateral acceleration, roll rate, yaw rate and speed were recorded. The steer axle and rear axis paths were marked using a water-soluble paint sprayed from pressure sprayers operated from the cab. The locations of the paint trails left by the trial vehicle were measured using standard electronic theodolite techniques.

## **2.2 Assumptions used in determining offtracking**

The relationship between curve radius, vehicle speed and offtracking was determined by conducting simulations at two speeds on curves with radii ranging from 50 m to 250 m. The following assumptions were used in determining the simulation speed and curve radii.

- Each curve was simulated at a speed that produced a lateral acceleration at the prime mover of 0.22 g and 0.055 g, where 0.22 g is the lateral acceleration threshold upon which curve advisory speeds are calculated and 0.055 g corresponds to half the advisory speed.
- Simulations were performed for vehicles negotiating 90 degree curves on a flat road.
- The curves were constructed from Cornu spirals (Faux and Pratt, 1981) as, ideally, curves on the SH network approximate Cornu spirals (Austroads, 1997).
- Banked road speed was related to flat road speed by  $v_b = \sqrt{v_f^2 + gR\theta}$ , where  $v_b$  and  $v_f$  are the banked flat road speed respectively,  $g$  is acceleration due to gravity,  $R$  the curve radius and  $\theta$  the banking on the road.

## **2.3 Cost of Curve and Roundabout Modifications**

### **2.3.1 Curve Modifications**

Each curve on a designated network of routes was characterised by three parameters, the minimum radius of curvature of the curve  $R$ , the length of the curve  $l$ , and the existing road width  $w$ . Curves with only a small deflection angle were ignored.

Curve widening was deemed to be necessary if:

1. The increase in offtracking between baseline and proposed vehicles was greater than the distance 'A' (see Table 2) and,

2. Current corner seal width was less than the distance ' $2(MSP)+B+2C$ ', where MSP is the Maximum Swept Path, B is the vehicle to seal edge distance and C the inter-vehicle spacing, (see Table 2 and Figure 3).

Three road widening options were investigated (Table 2) with each successive option requiring more road widening and therefore greater cost.

Parameter costs were derived that could be applied globally to sections of road. Five terrain types have been considered,

- Mountainous - Difficult (longitudinal grade > 6%)
- Mountainous - Average (longitudinal grade > 6%)
- Hilly - Average (longitudinal grade 3 - 6%)
- Flat - Average (longitudinal grade < 3%)
- Flat - Softwidth. (longitudinal grade < 3%)

Because the extent of widening required is dependant on the radius of the curve, curve deflection angle and the existing road width, parameter costs per metre run (\$/m) were determined for widening the road by 0.5m, 1.0m and 1.5m with the widening applied through tapers of 10m, 20m and 30m respectively at each end of the curve.

The costs of widening included the following as appropriate

- Site clearance, traffic control
- Excavation, fill
- Road construction ( subbase, basecourse, roading, road marking)
- Gabions, drainage, guardrail, fencing, grassing
- Traffic sign relocation
- Fixed percentage for establishment, contingency & design fees

A field survey using Total Station survey techniques was carried at thirteen selected sites to confirm the parameters used to estimate the curve widening costs. The sites chosen for the field survey represented a cross-section of the terrain types.

### **2.3.2 Cost of Roundabout Modification**

Three existing roundabouts that represented the size variation of typical roundabouts on the SH network were chosen and the modifications and costs required to accommodate the proposed heavy vehicles were determined. The corresponding cost of modifying a roundabout of arbitrary size was then estimated by interpolating between the costs for modifying the three representative roundabouts.

It was assumed that widening would be achieved by reducing the diameter of the non-mountable central island and moving the outside kerbs out. This would allow heavy vehicles to track over the mountable central ring, if required, while directing the remainder of the traffic around lanes similar to those currently marked.

The costs of widening included the following as appropriate

- Location (urban, industrial, rural)
- Site clearance, Excavation, Traffic control
- Kerb (remove and replace), Concrete apron (centre)
- Road construction (subbase, basecourse, roading (asphaltic concrete), road marking)
- Footpath (asphaltic concrete), Topsoil/grassing
- Traffic sign relocation, Light pole relocation
- Fixed percentage for Establishment, Contingency & Design fees

## **2.4 Inventory of Designated Routes**

Routes on the SH network where increases in freight carrying capacity would give considerable advantage were identified. The rationale was to connect the major cities, ports and industrial areas. This included access corridors to and from the identified industrial areas.

## **2.5 Road Geometry Databases**

Two databases that record geometric features on the SH network were used. The Road Geometry Database (RGDAS) which records x, y and z co-ordinates, horizontal gradient, vertical gradient, curvature and location identifiers. RGDAS data exists for the entire SH network and was last updated in 1992. The second database was constructed by linking the Road Asset Maintenance and Management (RAMM) and Transit NZ geometry databases such that the number of lanes, lane width, seal width, cross slope, radius, gradient and distance were available at 10 m intervals for the entire SH network. The information in this database was updated in late 1998. This was used to identify the curves and roundabouts on the designated routes.

## **2.6 Evaluation Tool**

The offtracking data, curve modification cost per terrain type, route data and road geometry data were linked programmatically and combined with a graphical user interface (using Visual Basic) that allowed the cost on individual network routes for different vehicle and road widening options to be evaluated. The number of curves to be modified on each network sector was also determined.

# **3.0 RESULTS AND DISCUSSION**

For the range of curves, speeds and vehicles simulated the largest offtracking occurred when the simulation speed was half the advisory speed, with the rear axis inboard offtracking. Compared to the baseline vehicles the two B-train variants analysed had longer wheelbases and an extra axle, both of which reduced the tendency to outboard offtrack. Results from the field trial confirmed this with no outboard offtracking occurring on the highway corners, even with lateral accelerations above 0.22 g and speeds up to 80 km/h while cornering.

Field trial results compared well with tracking predications made by the simulation model for both low and high speed cornering tests with results being within the measurement error tolerance of the surveying technique used to measure the tracking paths, see Table 1. The results for the lower speed 90 degree intersection and 90 degree roundabout tests were also compared against results from a creep speed only model (purely kinematic). The results from the TERNZ simulation model were the same at speeds under 12 km/h and superior for speeds from 12 km/h – 20 km/h, see Table 1.

A limitation of using half the advisory speed to determine the offtracking on all corners is that the estimated road space requirements on flat and rolling terrain will be greater than required. Speed surveys suggest HV take corners between 10 km/h – 15 km/h over the advisory speed and therefore inboard offtrack less or even outboard offtrack. For mountainous terrain the opposite is true with HV possibly traversing corners at less than half the advisory speed and therefore offtracking more than the amount used for this study. A possible refinement of the methodology would be to link the offtracking requirements to the terrain type.

From Table 3 and Table 4 the significant increase in cost and number of curves requiring modification can be seen as the inter-vehicle spacing and vehicle to road edge distance is increased for Options 1 – 3. If it is assumed as in option 3 that existing curves on the SH network were designed to accommodate the current size of vehicles and nothing larger then the costs for the 21 m B-Train will be over 3.3 times that required for the spacing requirements in option 1.

The results highlight the need for further research into what inter-vehicle and vehicle to road edge distance gives satisfactory safety margins for heavy vehicles. Ongoing research into the behaviour/capabilities of HV drivers engaged in the driving task and analysis of HV crash statistics are being used to add further insight into road space requirements. Observations made by video-taping the tracking performance of the trial 26.5 m, 62 tonne B-train and a standard 20 m 44 tonne B-train traversing the same section of SH was that the number of times a combination left its intended lane was more strongly related to the driver than to the vehicle tracking performance.

Results from the geometric evaluation of the network, in terms of cost to upgrade per vehicle option per network sector were combined with safety related, pavement and bridge upgrade costs in the economics component of the HVL project see Figure 1.

Current research efforts in developing a combined driver/vehicle/road model, including driver like behaviour, vehicle, engine and driveline dynamics and accurate three dimensional representations of multi kilometre stretches of the SH network will greatly improve required road space calculation and road design consistency. The road trial also revealed fundamentally different philosophies in the New Zealand and Australian road regulations regarding the expected way a driver should approach a 90 degree right hand turn on a dual circulating roundabout.

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## 5.0 TABLES AND FIGURES

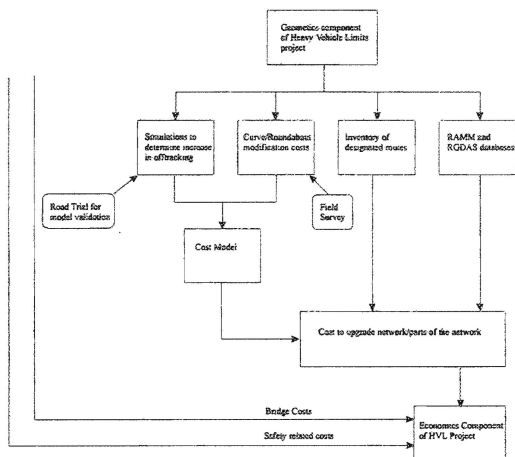
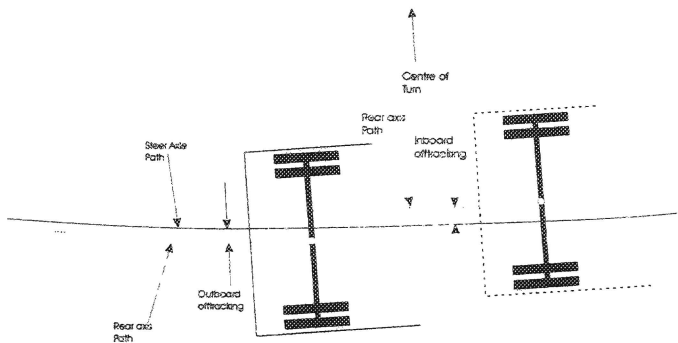
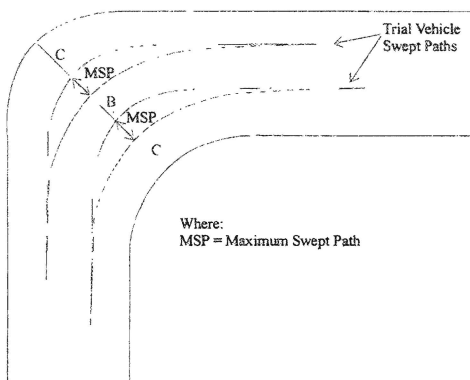


Figure 1: Structure of Geometrics component of HVL project and relation to other components.



**Figure 2: Inboard and Outboard offtracking**



**Figure 3: Road space requirements**

**Table 1: Field trial and simulation results**

Test	Offtracking Surveyed (metres)	Offtracking – Simulation (metres)	
		TERNZ model	Low Speed Model
90 degree roundabout	4.341	4.395	4.59
90 degree intersection	5.47	5.449	5.73
High speed, run 1	0.552	0.5404	-
High speed, run 2	0.3108	0.3273	-
High speed, run 3	0.202	0.2102	-

**Table 2:** Coefficients for corner widening calculation

Option	A (metres)	B (metres)	C (metres)
1	0.25	1	0.5
2	0.15	2	1
3	0	Note 1	Note 1

Note 1: Option 3 assumed that any increase in offtracking would require an increase in road curve widening costs that vary depending on the terrain, extent, length of widening and the position of widening (inside - cut into hill, outside - fill over edge).

**Table 3:** Normalised cost of modifying specific network of routes for 21 m and 25 m B-train variants.

Option	Cost for modifications for 21 metre B-train	Cost for modifications for 25 metre B-train
1	1.00	2.32
2	2.39	7.06
3	3.34	11.44

**Table 4:** Number of curves that require modification on the network of routes.

Option	trial vehicle	Number of curves to be modified
1	21 metre B-train	376
1	25 metre B-train	817
2	21 metre B-train	927
2	25 metre B-train	2531
3	21 metre B-train	1247
3	25 metre B-train	3784

**Table 5:** Normalised cost of modifying roundabouts on SH network for 21 m and 25 m B-train variants

Vehicle	Cost of modifying roundabouts on the network of routes
21 metre B-train	1.00
25 metre B-train	1.09

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