The Influence of Highway Geometry on Vehicle Stability in New Zealand

ABSTRACT

The interaction between road geometry, heavy vehicle stability and manoeuvrability performance, and driver behaviour has been investigated by computer simulation and full-scale testing.

Methods have been developed to convert the measured road geometry data into a form suitable for vehicle simulations. The road geometry data describes all major highways of the New Zealand road network in three-dimensional space.

A new driver model, intended to control vehicle speed during simulations on hilly terrain, is presented. Comparison with preliminary tests shows promising results.

Heavy vehicle simulations have long been used in New Zealand to analyse vehicle stability. This paper describes the advances being made by combining the road geometry data and driver model developments with the vehicle modelling capability.

A case study involving logging trucks is included.

INTRODUCTION

The three principal areas that influence the safety and efficiency of a road vehicle are:

i) road environment;
ii) vehicle performance; and
iii) driver decisions.

To create a realistic model of New Zealand heavy trucks, a simulation that incorporates all three of these areas is under development. Each of the three areas, and the progress being made therein, is discussed below.

1. ROAD ENVIRONMENT

NZ TERRAIN

New Zealand is a long, narrow island nation with a hilly topography. Consequently, the State Highway network contains many sections with winding, cambered corners (*great for motorcycle aficionados, but demanding for other road users*) and long ascents and descents.

DESCRIPTION OF ROAD GEOMETRY DATABASE

The State Highways in New Zealand are administered by Transit New Zealand. A road geometry survey was undertaken by the Australian Road Research Board using an instrumented vehicle. During the survey, the following data was obtained at 10 metre intervals along the road:

- distance travelled from datum;
- distance East from datum;
- distance North from datum;
- altitude change from datum;
- gradient;
- vertical curvature;
- horizontal curvature;
- cross-slope;
- survey vehicle speed.

The road geometry database comprises a set of "spreadsheet"-style tables for each portion of surveyed State Highway. Table 1 contains a short sample extract from one file.

To use the data from the road geometry database in a computer simulation it must first be converted from a road centre-line in 3-D space into a surface plot. Figure 1 shows an example of a 3-D surface plot.

2. VEHICLE SIMULATION

Traditionally, heavy vehicles have been analysed using constant speed, flat plane models, such as *YawRoll* (Gillespie, 1982). They give good indications of the stability performance of different truck-trailer configurations under varying load conditions.

In recent years, multi-body software such as *AutoSim* (written by Mike Sayers of UMTRI), and advances in computer speed and capacity has significantly widened the scope for the generation and use of more comprehensive vehicle models.

An example of the combination of a complex vehicle model and a 3-D road surface (off-highway) was the stability and manoeuvrability research undertaken on a vehicle intended to transport tree-length (30m to 35m) logs, Figure 2. The forest companies have found that

Table 1 Sample of Road Geometry Data

ODO km	EAST km	NORTH km	ALT km	BRG rad	G %	V 1/km	H 1/km	X %	S m/s
23.7000	3.5141	18.3133	-0.1019	-0.781	-8.1	0.5	5.3	6.0	18.7
[illegible]100	3.5073	18.3206	-0.1027	-0.721	-8.3	0.2	6.7	6.9	18.4
[illegible]200	3.5010	18.3284	-0.1035	-0.644	-8.2	-0.1	8.1	8.2	18.0
23.7300	3.4953	18.3366	-0.1043	-0.547	-8.2	0.0	11.2	9.0	17.4
23.7400	3.4906	18.3454	-0.1051	-0.431	-8.3	-0.3	12.6	9.2	17.4
23.7500	3.4871	18.3548	-0.1059	-0.299	-8.0	-0.2	13.8	8.7	17.5

significant efficiency gains are possible when log length cutting decisions are made in the processing yard rather than in the forest.

Of particular interest was optimum vehicle configuration for safe operation and the manoeuvring characteristics on worst-case off-highway road sections.

SIMULATION MODEL

A comprehensive model of the laden vehicle was developed using *AutoSim*. While based on a current vehicle configuration, using a sliding pole to steer the jinker trailer, this vehicle had a significantly longer pole and a very large rear overhang. Total laden vehicle mass was 70,400 kg.

3-D TERRAIN

Incorporating the 3-D road capability was the greatest technical hurdle. This project demonstrated that extending the flat road scenario to include real terrain is not a trivial exercise. However, since the long log project was more concerned with low-speed manoeuvring through the hilly sections, rather than highway-speed stability over such roads, the inertial effects became less critical in the vehicle model, simplifying matters in this specific instance.

FULL-SCALE TRIALS

Transducers and computer data acquisition equipment were installed on the vehicle to measure:

i) forward speed
ii) articulations angles
iii) truck roll and yaw rates
iv) trailer roll and yaw rates.

Data were recorded for a number of prescribed manoeuvres and during normal operation along demanding private gravel and tarmacadam roads. Within the constraints of gross vehicle mass, engine power and available road length it was only possible to undertake dynamic stability tests at 60 km/h. This is a typical operating speed for these off-highway log trucks when laden.

RESULTS

Stability performance during a simulated rapid path change manoeuvre (single lane-change producing 0.15g lateral acceleration) at 80 km/h was evaluated and compared with a conventional off-highway A-double. Table 2 summarises the results.

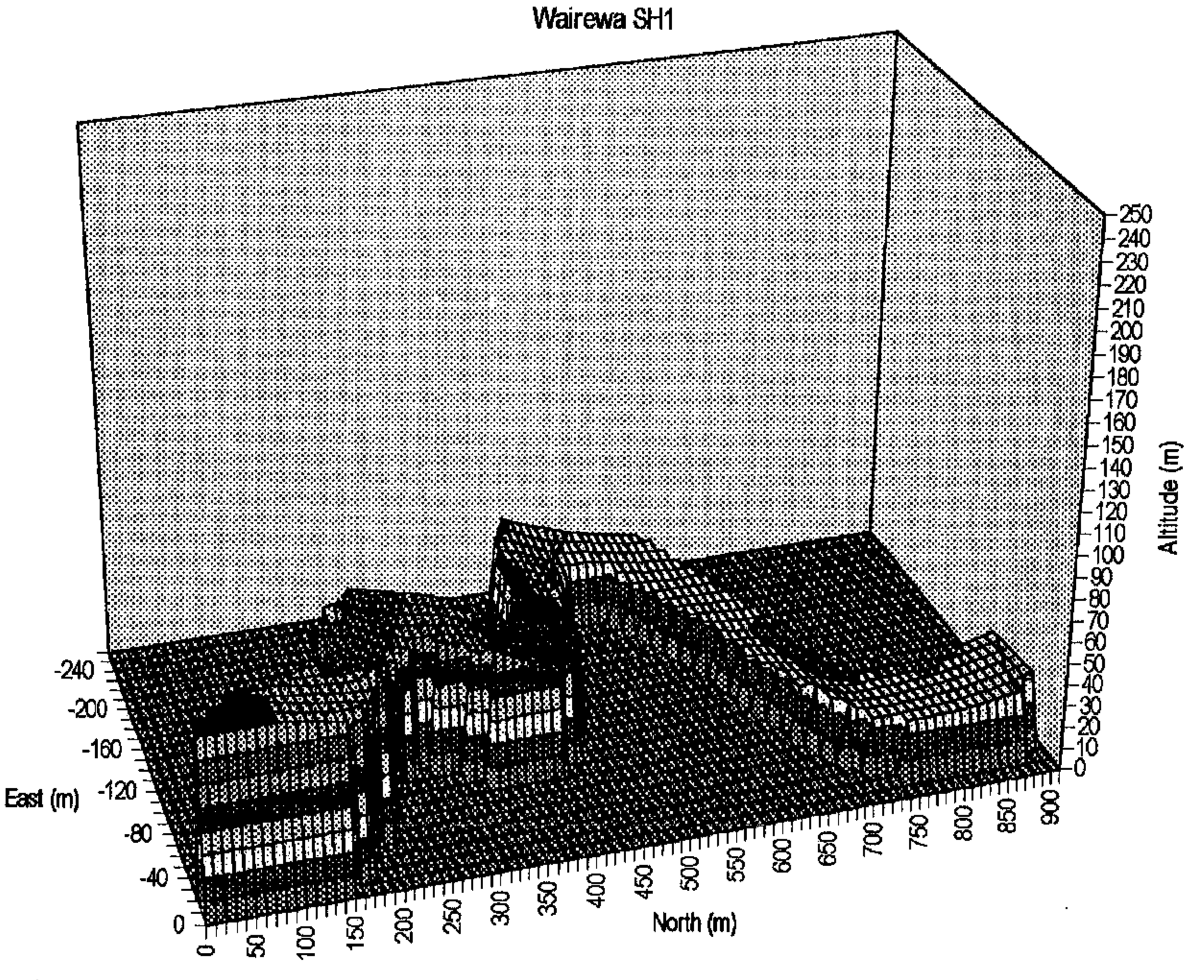

Figure 1 Example surface plot of 3-D road geometry. (State Highway 1 approaching Wairewa northbound.)

	Long Log Vehicle	Off-highway A-double	Target Range
Dynamic Load Transfer Ratio	0.41	1.0	≤0.6
High-Speed Transient Offtracking (m)	0.86	1.23	≤0.6

The long length of the "long log" payload translates into a lower CG height than a conventional payload. This is evident in the superior Dynamic Load Transfer Ratio results for the long log vehicle. High-Speed Transient Offtracking benefits from the reduction in articulation points.

Lengthening the sliding pole was found to improve the stability performance.

IMPLEMENTATION

As usual, such results are implemented quickly. The analysis and report (White, 94) satisfied the stability and safety concerns. A number of logging trucks of this design are now working in New Zealand forests.

LOGGING TRUCK STABILITY

Recent logging vehicle measurement and stability analysis highlighted stability deficiencies in conventional logging truck configurations.

Part of the problem is operational (stability degrades rapidly with overloading, since additional payload must be placed on top of the legitimate load). The other part of the problem is an engineering issue: any success in lowering the height of bolsters is directly reflected in improved stability.

In this regard, the increasing use of low profile tyres is an encouraging trend.

WEBBING STRAPS FOR LOG LOAD SECURING

In response to requests from some sectors within the logging industry, log load securing tests were undertaken comparing chains and web straps. Representatives from LIRO, IRL, LTSA and OSH witnessed the tests.

Three webbing straps could restrain a load of wet, peeled logs. Two webbing straps could not. The same load was successfully restrained with one chain. See Figures 2 and 3.

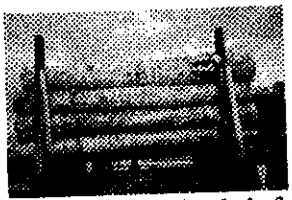

Figure 2 Test bunk before braking tests

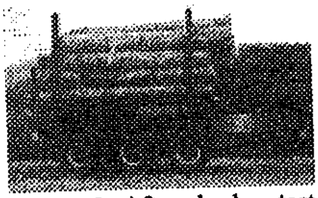

Figure 3 After brake test with one web strap

TAPLEY METER USAGE

Industrial Research Ltd provided instrumentation to measure truck speed and deceleration. It uses a sophisticated non-contact light sensor and intelligence to determine vehicle speed and send data to a laptop computer.

Measurements from a Tapley meter were compared for three braking tests. Table 3 contains the results.

Table 3 Tapley meter comparison

Test No.	Datron (g)	Tapley (g)	Tapley position	Tapley Error (%)
12	0.45	0.59	in cab	31
13	0.49	0.60	in cab	22
14	0.47	0.47	on chassis	0

As can be seen, the cab-mounted Tapley meter error is large and anti-conservative — that is, the meter indicates the vehicle is braking harder than it actually is. (This is probably due to the sprung mounted cab deflection absorbing energy during the braking event, and releasing it again as the braking finishes.)

When the Tapley meter is mounted on the chassis, accuracy is excellent.

3. DRIVER MODEL

DESIGN PHILOSOPHY

Driver and vehicle interaction has been a subject of extensive study for the past few decades (Forster, 1991; MacAdam, 1980; Guo and Guan, 1993). The interaction between the known dynamics of the vehicle and unpredictable human behaviour is a difficult subject of study. Although human behaviour is not deterministic, it can be estimated for a normal person under certain constraints.

PREVIEW CONTROL MODEL

The model under development includes a realistic driver-vehicle interaction. The driver-vehicle system is

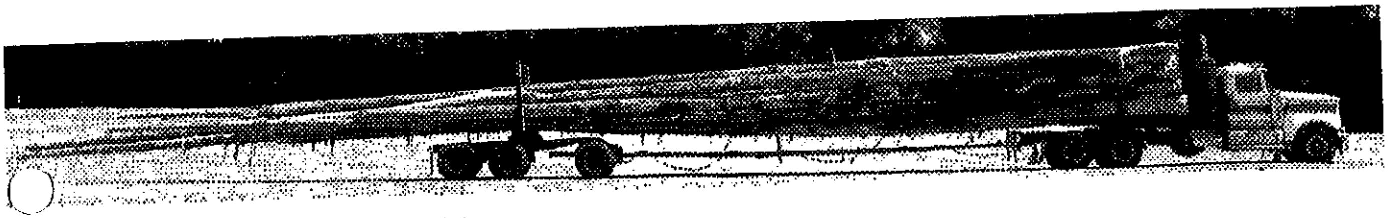

Figure 4 Trial "Long Log" Vehicle

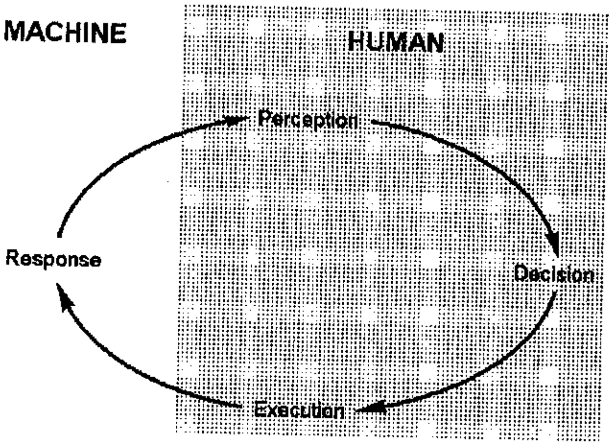

Figure 6 Driver Model Loop

considered to be a closed loop system. Only four major points are considered on the continuous cyclic process:

i) Driver **Perception**.
ii) Driver **Decision**.
iii) **Execution** (path correction and/or speed control).
iv) **Mechanical Response** of the system.

The cycle continues as **Perception - Decision - Execution - Response - Perception - Decision**... as shown in Figure 5. The driver-vehicle system is a combination of mechanical and biological processes. The mechanical process is active only for the **Mechanical Response** phase of the cycle. Whereas, the biological processes are active during the **Perception - Decision - Execution** phases of the cycle.

The general idea of the driving process (or any other human controlled mechanical system) is shown in Figure 5. In this figure the driver's task is separated into three parts, the perception of the current status of the mechanical system, the course and speed decision process and applying the driver inputs to the vehicle. The function of the mechanical system is only to transfer the driver's control into output response. There is always some time involved in each phase on this cycle. The times are denoted by:

t_P, perception time;
t_D, decision time; including reaction time;
t_E, execution time, muscle activity; and
t_M mechanical time, in converting control signals to output by the mechanical system involving such elements as linkages, air pressure, and hydraulics in the vehicle.

Perception time and decision time depend entirely upon the activity of the brain. During the human part of the cycle the mechanical system continues to operate with its control setting from the previous **Execution** phase. The total cycle time T is the algebraic sum of the individual times:

$$T = t_P + t_D + t_E + t_M \qquad (1)$$

The driver model assumes this loop is progressing continually, with the driver perceiving the driving situation, deciding on control actions, executing the decisions by manipulating the driving controls, then the vehicle responds.

In Equation (1), t_M is considered constant, depending only upon the mechanical system and is assumed to be short relative to the human response time. In the real world, the mechanical response time can be long, catching out a novice driver who thinks the vehicle is not responding enough and overcorrects. This capability is not included in our present model.

However, t_P, t_D and t_E can vary. These values can increase or decrease but in the same ratio. For example, in a very relaxed state of the driver, the values of t_P, t_D, and t_E are large. However, if the driver is over-cautious and stressed, the values of t_P, t_D, and t_E will tend to be small. This situation is shown in Figure 5.

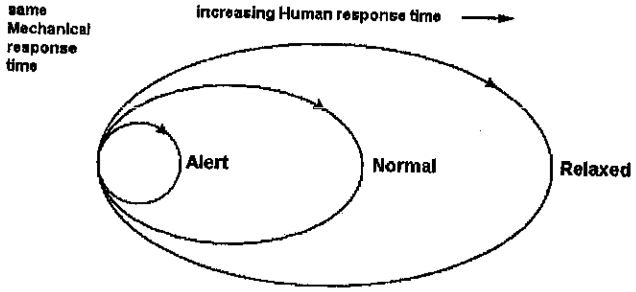

Figure 5 Driver Attentiveness Affects Response Time

It is therefore possible to split up the cycle into two components, viz.

i) Mechanical part, involving time lag, t_M, and
ii) Human part, involving time t_H, the algebraic sum of t_P, t_D, and t_E. Time, t_H, can also be regarded as the perceptual and neuromuscular lags in the human controller.

Hence equation (1) reduces to:

$$T = t_H + t_M \qquad (2)$$

For a normal driver, the degree of concentration and alertness — and hence the human response time of the cycle — varies with the road conditions (such as traffic density, type of intersections) and the environment (including weather and lighting). Based on the driver's interpretation of the driving conditions, his/her own driving skill and the vehicle's capabilities, the driver intuitively estimates the risk factor. On a divided highway with little traffic and good weather the risk factor is very small and hence the typical driver will be relaxed and human response time t_H is large.

RISK TIME

We further define a time, t_R, called Risk Time. This is the time after which, the driver thinks, the vehicle could reach disaster on the road. The Risk Time is estimated by the driver from the vehicle trajectory and anticipation of potential hazards or situations requiring corrective action. Such situations include:

i) hazard or traffic signal requiring the vehicle to stop;
ii) vehicle following another vehicle keeping a safe distance or time lag;
iii) hazard requiring an avoidance manoeuvre;
iv) hazard beyond lane boundary requiring steering control to keep the vehicle in its designated lane.

For each situation a driver will estimate the time available before an avoidance action is essential. This Risk Time can be very small in some circumstances, for example a child darting onto the road.

A vehicle at high speed will have a short Risk Time. Conversely, a vehicle at slow speed will have a long Risk Time. The Risk Time is limited by the driver's visibility and anticipation.

The length of the human part of the cycle is dependent upon the Risk Time: as the Risk Time is perceived to decrease (indicating increasing risk of collision), the driver tends to concentrate harder. We assume that the human response time, t_H, is proportional to the risk time.

$$t_H = k \times t_R \qquad (3)$$

The value of k in equation (3) depends upon the ability of the driver, which can vary between $k = 0$ to $k = 1$. For an expert driver the value of k, the Human Ability Coefficient, is small. For a novice driver, k is large.

CRASH CONDITIONS

If the Risk Time is less than the Mechanical Response Time, t_M, the crash will take place.

If the Human Ability Coefficient, k, is large, there will only be time for a few cycles of the driver feedback process during the Risk Time available and slight error, which is always present in such systems can bring the system to disaster.

If, on the other hand, k is small, that is, a good driver, there will be many cycles of the driver feedback process during the Risk Time. Any human error made in one cycle can be corrected in the next one and such a system will be highly controlled one.

Thus, the greater the number of cycles during the Risk Time the better (more reliable) is the control of the Human - Machine system.

DRIVING STRATEGY

There are many different driving control strategies. They include:

i) minimising journey time;
ii) minimising distance travelled;
iii) minimising fuel consumption;
iv) minimising travel risk.

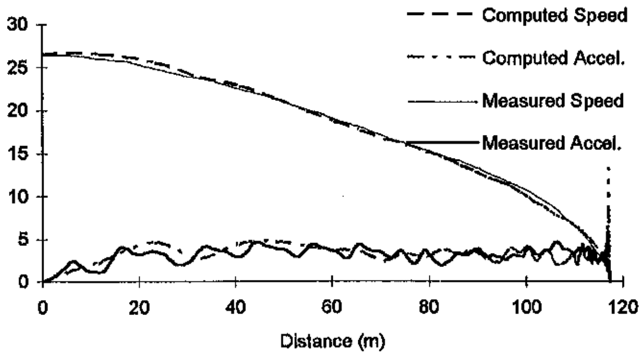

Figure 7 Comparison of Measured and Predicted Performance (acceleration in m/s^2, velocity in m/s)

So far as the value of t_H is concerned the human brain is very flexible — it can work relatively slowly in the relaxed state and very fast during an emergency. If the state of the brain is conscious, Perception Time and Decision Time are large. However, in the subconscious state of the brain, the Decision Time becomes extremely small — of the order of 10^{-12} second. The minimum value of t_H is limited by the Execution Time, since the muscle reflex is not as fast as the brain.

DRIVER ERROR

The driver is assumed to be imperfect. Driver errors in each phase of the human response cycle are possible. Errors in the mechanical system occur when the vehicle develops a fault. Mechanical faults are assumed to be negligible in this analysis and only the human factors are considered.

Errors during Perception, Decision and Execution can be considered as one Human Error, represented by ε. The Risk Time, t_R, Driver Ability Coefficient, k, and Human Error, ε, are the fundamental parameters employed in this driver model.

COMPARISON WITH TEST DATA

Validation of these theories was undertaken for one case — braking to a stop.

Brake testing was conducted in a van on a flat straight road. Different drivers were asked to stop at a marked point from a uniform initial speed. Vehicle speed was measured using a Datron non-contact transducer sampled at 100 Hz. The measured data from a typical test is plotted in Figure 7, together with the computed values.

The agreement between the computed and experimental results is good, which supports the basic philosophy of this driver vehicle model.

FUTURE RESEARCH

Our future vehicle performance projects are dependent on developing the 3-D terrain capabilities satisfactorily. That capability will then allow Industrial Research Ltd to investigate the effect of driver and vehicle parameters on safety, transport efficiency, and environmental effects.

DRIVER COMPARISON

Present research has focused on differences between drivers in the same heavy vehicle on the same highway. This project is on-going, and does not yet have findings to report.

ENVIRONMENTAL EFFECTS

A project underway is examining the environmental effects of vehicles and how changes to route, driver and vehicle affect vehicle emissions.

CONCLUSIONS

The need for real-world terrain data is examplified by a stability investigation of a log truck carting tree-length logs.

The New Zealand Road Geometry Database is a valuable asset for vehicle simulation on actual highways.

A driver model has been developed with the intention of controlling not only vehicle direction, but also vehicle speed. Preliminary testing has demonstrated good correlation with physical tests.

Upcoming research will extend the model to handle speed control on simulated hilly terrain.

REFERENCES

Forster, H. J. (1991). VDI Berichte NR, 916.

Gillespie, T.D. & MacAdam, C.C. (1982) *Constant Velocity Yaw/Roll Program*, UMTRI-82-39.

Guo, K. and Guan, H. (1993). *Modelling of Driver/Vehicle Directional Control System* in Vehicle System Dynamics, **22**, 141-84.

MacAdam, C. C. (1980). *An Optimal Preview Control for Linear Systems*, J. Dyn. Sys. Measur. Control, **102**, 188-93.

White, D.M. (1994) *Long Log Transport — Stability and Safety Implications*, Industrial Research Ltd report 282 to Logging Industry Research Organisation and Forestry Corporation.

White, D.M. & Thakur, K. (1995) *Stability in the Real World — Influence of Drivers and Actual Roads on Vvehicle Stability Performance*, 4th Int. Symp. On Heavy Veh. Weights and Dimensions, Ann Arbor, USA.

ACKNOWLEDGMENTS

Transit New Zealand kindly provided the road geometry data for the sections of State Highway on request.

Logging Industry Research Organisation (LIRO) were instrumental in arranging testing and measuring of logging vehicles. LIRO and Forestry Corporation gave permission for the dissemination of details of the Long Log study.

UMTRI produced *YawRoll* and *AutoSim* programs used in this investigation. UMTRI developed much of the long log vehicle AUTOSIM model.

The Public Good Science Fund administered by the Foundation for Research Science and Technology funded much of the new development work described in this paper.