ANNEX: SITE DESIGN FOR HEAVY VEHICLE FACILITIES

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AN IMPORTANT NOTE FOR THE READER

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CONTENTS

EXECUTIVE SUMMARY

This report is an Annex to Transit New Zealand Research Report No. 32, *"Site design for heavy vehicle facilities"*. This Annex summarises the seven individual research studies (unpublished) that were undertaken between 1985 and 1990 and from which Transit New Zealand Research Report No. 32 was prepared.

The summaries of the seven research studies are presented in this Annex as follows:

- **New Zealand Heavy Vehicle Fleet**

Analysis of dimensional characteristics of trucks and buses using New Zealand roads (surveyed between 1984 and 1989).

- **Initial Choice of Design Heavy Vehicles**

Interpretation of the results of the heavy vehicle surveys and the initial range of "design" vehicles chosen as suitable for the purpose of the project.

- **Trials to Confirm Accuracy of the Swept Path Computer Program**

Results of field trials which used a range of heavy vehicles to compare actual "tracking curves" with those simulated by a computer program for vehicles of the same dimensions.

- **Supplementary Field Trials**

Results of field trials with 3-point turns, made by heavy vehicles when using vehicle loading docks.

- **Trials to Establish Clearances Required by Heavy Vehicles**

Results of field trials with trucks and a tour coach to determine the tolerance required outside the theoretical vehicle path to make manoeuvring comfortable for the driver.

- **Trials to Establish Variations in the Position of Heavy Vehicle Rear Axes**

Results of a survey of heavy vehicles to determine the amount of variation in the position of the rear axis about which a vehicle turns.

- **Trials to Determine the Effect of Loading on a Heavy Vehicle's Rear Axis**

Results of field trials to compare the turning performance of trucks when unladen, half-laden (with load at different positions on the deck) and laden.

ABSTRACT

This report is an Annex to Transit New Zealand Research Report No. 32, *"Site design for heavy vehicle facilities"*. This Annex summarises the seven individual research studies (unpublished) that were undertaken between 1985 and 1990 and from which Transit New Zealand Research Report No. 32 was prepared.

1. INTRODUCTION

A project (GM/11) was commissioned in 1984 by the former National Roads Board (now Transit New Zealand) with the aim of preparing a set of guidelines to assist architects and site planners in the design of on-site facilities for heavy vehicles. These heavy vehicles include a wide range of trucks, buses and special purpose vehicles (such as fire engines).

The site design recommendations and "tracking curves" have been developed, between 1985 and 1990, after extensive research of the characteristics of heavy vehicles used in New Zealand. They are based on the collection of international data, the development of a computer model to simulate vehicle "tracking curves", and surveys and field trials to confirm some of the theoretical work. The final report (updated to 1993) is published as Transit New Zealand Research Report No. 32, *"Site design for heavy vehicle facilities"*.

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- **Supplementary Field Trials** (Beca Carter Hollings & Ferner Ltd 1988a,b)

Results of further field trials which concentrated on the 3-point turns that are made by heavy vehicles when using vehicle loading docks.

- **Trials to Establish Clearances Required by Heavy Vehicles** (Traffic Planning Consultants Ltd 1988)

Results of field trials with trucks and a tour coach to determine the tolerance required outside the theoretical vehicle path to make manoeuvring comfortable for the driver.

- **Trials to Establish Variations in the Position of Heavy Vehicle Rear Axes** (Traffic Planning Consultants Ltd 1989a)

Results of a survey of heavy vehicles passing through a testing station to determine the amount of variation in the position of the rear axis about which a vehicle turns.

- **Trials to Determine the Effect of Loading on a Heavy Vehicle's Rear Axis** (Traffic Planning Consultants Ltd 1989b)

Results of field trials which compared the turning performance of trucks when unladen, half-laden (with load at different positions on the deck) and laden.

2. NEW ZEALAND HEAVY VEHICLE FLEET

2.1 General

The information in this section is, unless stated otherwise, fully covered in the report produced for Project GM/11 Stage 1 (Beca Carter Hollings & Ferner Ltd 1987a).

2.2 Heavy Vehicle Surveys

Data on variations of overall vehicle length in different classes of heavy vehicles obtained from several surveys (noted below) were analysed.

2.2.2 Ministry of Transport Photographic Survey (1984)

This survey measured the dimensional characteristics of trucks from photographs taken of passing traffic. The survey covered both urban and rural areas. An analysis of the data are shown in Table 2.1. The numbers of trucks measured were:

Urban areas	475 (from Auckland, Wellington, Christchurch)
Rural areas	451 (from Napier, Taupo, Masterton)

2.2.3 Franklin County Heavy Vehicle Survey

This survey (Ministry of Works & Development 1985a) recorded the lengths, weights, and commodities of all trucks and buses in the western district of Franklin County (Waiuku, Glenbrook, Pukekohe and Tuakau). Five sites were surveyed over five successive days, on both state highways and important rural arterial roads. An analysis of the data are shown in Tables 2.2 and 2.3. The numbers of vehicles measured were:

Trucks	1953
Buses	142

Table 2.1 Statistical summary of overall length (metres) of trucks, obtained from photographic survey of certain urban and rural areas (Ministry of Transport 1984).

Vehicle Type	Length (m)					Sample Size
	Mean	Std Dev^n	Minimum	Maximum	90th percentile	
Urban Auckland						
2-axle single unit truck	6.71	1.11	4.13	9.51	7.91	122
3-axle single unit truck	7.78	1.14	6.16	9.51	9.35	23
4-axle single unit truck	9.77	-	9.77	9.77	9.77	1
Truck & semi-trailer	14.36	1.84	10.42	16.91	16.49	39
Urban Wellington						
2-axle single unit truck	6.75	1.26	3.45	9.92	8.31	80
3-axle single unit truck	8.53	1.04	7.02	10.14	9.95	16
4-axle single unit truck	8.96	0.56	8.37	9.72	9.72	4
Truck & semi-trailer	12.96	1.53	10.16	15.65	14.76	21
Urban Christchurch						
2-axle single unit truck	6.61	1.00	4.40	9.37	7.84	148
3-axle single unit truck	8.37	0.93	6.58	10.07	9.59	34
4-axle single unit truck	9.24	0.52	8.64	9.54	9.54	3
Truck & semi-trailer	12.74	2.35	9.01	17.93	15.95	48
Combined Urban and Rural (Napier, Taupo, Masterton)						
2-axle single unit truck	6.68	1.09	3.45	9.92	7.92	396
3-axle single unit truck	8.47	1.00	6.16	10.54	9.52	121
4-axle single unit truck	9.22	0.46	8.37	9.77	9.74	14
Truck & semi-trailer	13.74	1.35	9.01	18.48	16.73	140
Truck & full trailer	17.38	2.04	7.46	20.49	19.19	182

Table 2.2 Statistical results of overall length (metres) of trucks, obtained from Franklin County Heavy Vehicle Survey (Ministry of Works & Development 1985a).

Vehicle Type[(a)]	Length (m)					Sample Size
	Mean	Std Dev^n	Mini-mum	Maxi-mum	90th percentile	
MCV	7.04	1.15	4.40	11.15	8.85	704
HCV1	8.29	1.24	5.65	12.90	9.75	279
HCV2-1	13.14	2.16	8.70	17.70	15.80	269
HCV2-2	17.65	2.40	12.00	20.40	19.35	583
HVC2-3	18.85	0.67	17.05	20.60	19.50	115
HCV2-4	19.60	0.10	19.50	19.70	19.70	3

(a) Footnote on p.13.

Table 2.3 Statistical summary of overall length (metres) of buses, obtained from Franklin County Heavy Vehicle Survey (Ministry of Works & Development 1985a).

Vehicle Type	Length (m)					Sample Size
	Mean	Std Dev^n	Mini-mum	Maxi-mum	90th percentile	
2-axle single unit bus	9.31	1.63	5.55	12.00	10.10	139
3-axle single unit bus	12.50	0.17	12.40	12.70	12.70	3

2.2.4 Hamilton Heavy Vehicle Survey (Ministry of Works & Development 1985b)

This survey was conducted at two locations on State Highway 1, one north and one south of Hamilton. An analysis of the truck data from the combined locations are shown in Table 2.4. (The sample for buses was too small to statistically analyse the data.) Trucks were measured and classified using the National Roads Board vehicle code. The numbers of vehicles measured were:

Trucks	816
Buses	18

Table 2.4 Statistical results of overall length (metres) of trucks, obtained from Hamilton Heavy Vehicle Survey (Ministry of Works & Development 1985b).

Vehicle Type[a]	**Length (m)**				**Sample Size**
	Mean	**Minimum**	**Maximum**	**90th percentile**	
MCV	7.12	4.40	10.10	8.80	279
HCV1	8.75	5.60	10.95	9.90	94
HCV2-1	13.85	8.70	17.50	16.60	156
HCV2-2	17.70	9.80	20.70	19.70	237
HCV2-3	18.95	17.00	20.80	19.60	39
HCV2-4	19.20	19.00	19.50	19.50	11

(a) Footnote on p.13.

2.2.5 Dunedin Heavy Vehicle Survey (Ministry of Works & Development 1985c)

This survey was of similar format to the Hamilton survey, and was conducted at two locations on State Highway 1, one north and one south of Dunedin. The data from the combined locations are shown in Tables 2.5 and 2.6. The numbers of vehicles measured were:

Trucks	1196
Buses	120

Table 2.5 Statistical results of overall length (metres) of trucks, obtained from Dunedin Heavy Vehicle Survey (Ministry of Works & Development 1985c).

Vehicle Type(a)	Length (m)					Sample Size
	Mean	Std Dev^n	Maxi-mum	Mini-mum	90th percentile	
MCV	6.78	1.20	4.30	11.40	8.28	556
HCV1	8.58	-	6.30	12.10	9.45	146
HCV2-1	13.66	-	7.80	20.90	16.60	155
HCV2-2	17.88	-	8.88	21.00	19.20	281
HCV2-3	19.17	-	18.90	21.00	19.73	55
HCV2-4	19.28	0.17	19.10	19.50	-	3

(a) Footnote for Tables 2.2, 2.4, 2.5

MCV	Medium commercial vehicle: 2-axle single unit truck
HCV	Heavy commercial vehicle:
HCV1	3- or 4-axle single unit truck
HCV2-1	Semi-trailer configuration
HCV2-2	Truck & trailer configuration
HCV2-3	A-train configuration
HCV2-4	B-train configuration

Table 2.6 Statistical summary of overall length (metres) of buses, obtained from Dunedin Heavy Vehicle Survey (Ministry of Works & Development 1985c).

Vehicle Type	Length (m)					Sample Size
	Mean	Std Dev^n	Mini-mum	Maxi-mum	90th percentile	
2-axle single unit bus	10.41	1.33	5.20	11.92	11.70	86
3-axle single unit bus	12.14	0.51	11.10	13.30	12.50	34

2.2.6 Otara Testing Station Heavy Vehicle Survey (Traffic Planning Consultants Ltd 1989a,b)

As part of the study of variations in the position of the rear axes, the overall dimensions of the following groups of heavy vehicles were measured:

2-axle rigid trucks	71
3- & 4-axle rigid trucks	41
Semi-trailers & B-trains	46
Trucks & trailers	19
Buses	22
Total	199

The distribution of overall length (metres) of the sampled 2-axle rigid trucks is shown in Table 2.7.

Table 2.7 The distribution of overall length (metres) of the sampled 2-axle rigid trucks.

Length (m)	**No. of Vehicles**	**Frequency (%)**
5.5 - 6.0	2	2.8
6.0 - 6.5	7	9.9
6.5 - 7.0	5	7.0
7.0 - 7.5	18	25.4
7.5 - 8.0	14	19.7
8.0 - 8.5	8	11.3
8.5 - 9.0	11	15.5
9.0 - 9.5	4	5.6
9.5 - 10.0	2	2.8

The distribution of overall length (metres) of the sampled 3- and 4-axle rigid trucks is shown in Table 2.8.

Table 2.8 The distribution of overall length (metres) of the sampled 3- and 4-axle rigid trucks.

Length (m)	**No. of Vehicles**	**Frequency (%)**
6.0 - 6.5	1	2.4
6.5 - 7.0	3	7.3
7.0 - 7.5	9	22.0
7.5 - 8.0	4	9.8
8.0 - 8.5	6	14.6
8.5 - 9.0	8	19.5
9.0 - 9.5	6	14.6
9.5 - 10.0	3	7.3
10.0 - 10.5	0	0.0
10.5 - 11.0	1	2.4

2.3 Bus Surveys

2.3.1 Introduction

In addition to the bus data obtained from the above mentioned surveys (shown in Tables 2.3 and 2.6) further data was obtained from bus operators and manufacturers.

2.3.2 Postal Survey of Bus Operators

A postal survey of bus operators in the greater Auckland area was carried out. Information requested about their buses included details of each model used, their age, passenger capacity, and dimensions.

Replies were received and details listed for buses operated by:

Railway Road Services
Newmans Coach Lines
Johnston's Blue Motors
Auckland Regional Council

2.3.3 Classes of Buses

From information obtained from bus operators, manufacturers and industry representatives, four classes of buses (mini-bus, midi-bus, urban bus, and tour coach) were identified. The classes and their respective dimensions (metres) are shown in Table 2.9.

Table 2.9 Typical dimensions (metres) for four identified classes of buses.

Bus Class	**Length (m)**	**Width (m)**	**Height (m)**	**Forward Length (m)**	**Overhang**		**No. of Axles**	**Approximate Turning Circle Diameter (m)**
					Front (m)	**Rear (m)**		
Mini-bus	7.55	2.15	2.78	5.45	1.12	2.10	2	13.0[a]
Midi-bus	9.34	2.36	2.89	6.50	1.70	2.84	2	15.0[a]
Urban bus	11.30	2.44	3.20	8.20	2.40	3.04	2	18.0[a]
Tour coach	12.30	2.50	3.50[b]	8.50	2.35	3.80	3	24.0[c]

(a) Kerb to kerb.
(b) Without any air-conditioning equipment. For roof-mounted air-conditioning equipment add approximately 0.3 m.
(c) Wall to wall.

Bus chassis which could be considered representative of each of the four identified classes are:

Mini-bus:	Hino RV or RB
Midi-bus:	Hino RR
Urban bus:	Hino RK, M.A.N. 21202 or 16240
Tour coach:	Hino CN or Volvo B10M

The distribution of the overall lengths (metres) of the buses sampled at the Otara Testing Station Survey (Traffic Planning Consultants Ltd 1989a,b) and shown in Table 2.10.

Table 2.10 The distribution of the overall lengths (metres) of the buses sampled at the Otara Testing Station.

Length (m)	No. of Vehicles	Frequency (%)
6.5 - 7.0	1	4.5
7.0 - 7.5	1	4.5
7.5 - 8.0	0	0.0
8.0 - 8.5	0	0.0
8.5 - 9.0	0	0.0
9.0 - 9.5	1	4.5
9.5 - 10.0	4	18.2
10.0 - 10.5	0	0.0
10.5 - 11.0	1	4.5
11.0 - 11.5	6	27.3
11.5 - 12.0	1	4.5
12.0 - 12.5	3	13.6
12.5 - 13.0	4	18.2

2.4 Special Purpose Vehicles Survey

2.4.1 Rubbish Trucks

A large range of types and sizes of rubbish trucks exist because each type has been designed for a specific use. However, the sizes of vehicles designed primarily for regular domestic rubbish collection are uniform enough to define two main types:

- **8.0 to 8.5 m overall length rigid truck**, with a 4.0 m to 5.0 m-long rubbish storage container.
- **12.0 m overall length semi-trailer**, with a 6.0 m-long rubbish storage container.

Industrial rubbish trucks are classified as jumbo-bin trucks, roll-on bin trucks, front-lift compaction trucks, or bulk refuse trucks.

Bulk transporters for rubbish are large semi-trailers, the dimensions of which approach the legal maximum. All other vehicles are based on a large single unit rigid truck.

2.4.2 Fire Engines

Fire appliances used in New Zealand are all rigid vehicles.

3. INITIAL CHOICE OF DESIGN HEAVY VEHICLES

3.1 General

Following consideration of the information summarised in Section 2, and the New Zealand traffic regulations current at the time (1987), a set of five truck and four bus "design" vehicles were chosen in preparation for the next stage of the project (Stage 2, Beca Carter Hollings & Ferner Ltd 1987b) which was to prepare typical vehicle "tracking curves" at various radii of turning.

Supplementary information for choosing these designs, obtained from the heavy vehicle survey results and from operators, was recorded in Project GM/11 Stage 1 report (Beca Carter Hollings & Ferner Ltd 1987a) and is summarised as follows:

3.1.1 Trucks

Studies of the dimensions of the New Zealand truck fleet showed that each vehicle combination has its statistical population distributed heavily towards the legal maximum. In some instances this maximum has been exceeded. Recent changes to the size limits of heavy vehicles have resulted in greater flexibility being incorporated in vehicle design with some increases being made to the overall length of particular vehicle combinations. As a result of the studies, the six "design" vehicle trucks initially selected for use in the guide had the following characteristics:

3.1.1.1 2-axle single unit truck or medium rigid truck

Trucks of this type, used in urban areas, are typically shorter by 0.5 m than those used in rural areas. In general the mean vehicle length was 6.9 m, with the 90th percentile vehicle length of 8.0 to 8.5 m.

This is the medium rigid truck "design" vehicle with a length of 8.0 m. It includes vehicles with dimensions that can be operated in reasonably confined urban environments.

3.1.1.2 Multi-axle single unit truck or large rigid truck

The mean length of these vehicles (8.4 m) is typically 1.5 m longer than the 2-axle single unit truck. Maximum vehicle length is between 9.8 m and 12.9 m, and the 90th percentile length is 9.7 m, which is approximately 1.0 m longer than the 2-axle single unit truck.

This is the large rigid truck "design" vehicle with a legal maximum overall length of 11.0 m. It has a forward length that is less than the legal maximum length. This vehicle has been chosen as it appears to most represent the range of vehicles that are in use in New Zealand at present.

3.1.1.3 Semi-trailer

These trucks differ throughout New Zealand. For example, the semi-trailers used in Wellington were some 1.5 m shorter than those used elsewhere. In most other parts of New Zealand, the semi-trailers were only slightly shorter than the maximum permitted overall length of 17.0 m, except in Christchurch and Auckland where the longest semi-trailer exceeded this length.

The trailer deck length, of approximately 12.2 m, is sufficient to accommodate one "40-foot" ISO shipping container. This semi-trailer "design" vehicle has a length of 17.0 m.

3.1.1.4 Truck-and-trailer

This vehicle had a mean length of 17.6 m, with a 90th percentile length that exceeded the legal maximum of 19.0 m in all four surveys. The maximum length was consistently between 20.5 m and 21.0 m.

An almost infinite number of combinations are possible by mixing various trailer sizes and truck configurations.

Depending on the truck deck length, this vehicle can transport two "20-foot" ISO shipping containers.

A truck-and-trailer has not been included as a "design" vehicle because it is believed its measurements would be contained within those for the semi-trailer or B-train.

3.1.1.5 A-train

The maximum length recorded was 20.8 m, and 90th percentile lengths are within 0.5 m more or less of the legal limit of 20.0 m.

An A-train has not been included as a "design" vehicle because it is believed its requirements would be contained within those of the semi-trailer or B-train.

3.1.1.6 B-train

The maximum length measured was 0.3 m inside the legal maximum of 20.0 m.

The B-train "design" vehicle has a length of 20.0 m.

3.1.2 Special Purpose Vehicles

3.1.2.1 Rubbish Trucks

For a single unit, the Medium Rigid Truck was used.
For a multi-axle unit, the Large Rigid Truck was used.
For a semi-trailer unit up to 12.0 m length, special "design" vehicles may be needed.

3.1.2.2 Fire Engines

For standard fire appliance the Medium Rigid Truck is used.
For an appliance with aerial scope, a Large Rigid Truck may be suitable.

3.1.2.3 Ambulances

Some information from Australia and New Zealand was available but ambulances were considered to be too small to be within the scope of this project.

4. TRIALS TO CONFIRM THE ACCURACY OF THE SWEPT PATH COMPUTER PROGRAM

4.1 Introduction

Field trials were carried out to confirm the accuracy of the swept path computer program which was developed to simulate the "off-tracking" behaviour of manoeuvring heavy vehicles. The vehicle types used were large rigid truck, semi-trailer and B-train. The results are covered in the report produced for Stage 2 of Project GM/11 (Beca Carter Hollings & Ferner Ltd 1987b).

All possible turning characteristics displayed by trucks were tested and the criteria to be met comprised:

1. Simulating the critical points of single and multi-unit vehicles executing a U-turn;
2. Simulating manoeuvres where the vehicle's complex geometric arrangement changes during the curve, e.g. S-bend, S-bend followed by U-turn;
3. Simulating reverse manoeuvres;
4. Reaching a correct state of "dynamic equilibrium".

Because of lack of time, not all of these criteria (1, 2, 3, 4) were carried out on each vehicle. However a representative set of trials was obtained.

4.2 Procedure

Swept paths were produced of the front and rear critical points of each heavy vehicle used in the trials. The critical points were:

1. Left front bumper;
2. Right rear axis.

Swept paths were obtained by marking the path followed by each of the critical points. This was done with the aid of guidance indicators and the path defined with shaving foam.

If part of the shaving foam trail was run over during complex manoeuvres, enough foam was trapped in the "pits" of the sealed surface to easily identify the path. These paths were then recorded using accepted land surveying procedures and equipment.

Following the trials, the recorded bearings and distances were downloaded into a computer for processing. The "tracking curves" were plotted at a scale of 1:200, and later used to verify the accuracy of the computer program.

Pairs of transparencies were produced for each trial so that the simulated track and the field track could be directly compared.

Should subtle differences between the simulated paths and those recorded in the field be present, it is believed that driver variation, field error, and the influence of tyre dynamics could be contributing factors.

4.3 Results

4.3.1 Rigid Trucks

720-degree Turn
The truck executed a clockwise 720° constant radius turn. The simulation showed a different diameter on the inside of the swept path to that measured. It was realised that the truck was not turning about its "theoretical" rear axis which is on the mid-point of the rear-axle pair. From the survey measurements it was calculated that the "effective" rear axis was 0.389 m forward of the theoretical position.

U-turn
Using the corrected rear-axis position already calculated, a good comparison was achieved, with some minor differences at the end of the "tracking curve" attributable to driver corrections.

S-bend
Using the corrected rear-axis position, some small differences of up to 0.3 m between field and simulated tracks were observed.

Reverse into Dock
Minor differences between the trials and simulation occurred, particularly for tracks of the front of the vehicle. Given the complexity of the manoeuvre, the simulation was considered to be sufficiently accurate.

4.3.2 Semi-trailer

U-turn
As with the rigid truck, the measured track of the tractor did not agree with the simulation. By moving the rear axis to the front axle of the tandem, a reasonably close comparison was obtained. Differences were up to 0.2 m.

4.3.3 B-train

U-turn
The swept paths of both the simulated and field tested vehicle show good similarity, with differences of 0.3 m and 0.5 m measured. Thus the program was deemed capable of performing simple movements of B-train vehicles. On this vehicle the theoretical and effective rear axes appeared to be the same.

S-bend
A comparison of the swept paths of both simulated and field trialled vehicles suggested a good degree of accuracy. However the swept paths of the right rear axis of the second trailer of the vehicle showed discrepancies, particularly at the apex of the U-turn.

4.4 Conclusions

Comparison of swept paths from both simulations and field trials indicate that the computer program:

1. is accurate;
2. can model "off-tracking" behaviour of heavy vehicles at slow speeds;
3. has such accuracy that it can detect discrepancies in "off-tracking" of heavy vehicles having axles with air-bag suspensions or incorrectly adjusted steering mechanisms.

5. SUPPLEMENTARY FIELD TRIALS

5.1 Introduction

The purposes of these field trials was to assess the validity of the simulated 3-point turns, assess the effect that driver "error" has on spatial requirements, and consider the effect on the turning capability of a truck by repositioning its rear axis. The resulting "tracking curves" are recorded in Parts A and B of Stage 2, Project GM/11 (Beca Carter Hollings & Ferner Ltd 1988a,b).

5.2 Procedure

Five vehicles were used in the trial: two rigid trucks, a semi-trailer, a B-train and a tour coach. The two rigid trucks were twin-steer.

A T-shaped area was marked out and vehicles not in use were parked along the boundaries to provide a sense of confinement as in a building. Drivers were not allowed to look through their rear windows when backing.

The tractor of the semi-trailer had an air-bag suspension for the rear axle (lazy axle). This enabled the position of the rear axis to be altered and its effect on turning characteristics to be measured.

5.3 Results

With familiarity of the turns and of the vehicle, drivers needed less room to make the manoeuvres. From observation, an estimate of the difference in driving accuracy when a driver was not familiar with the vehicle was of the order of ±0.5 m. It was recommended that the size of turning area be based on the manoeuvres executed by a driver who is familiar with the vehicle but not with the area.

The effect of shifting the rear axis was most noticeable during the reverse manoeuvre of a complex turn. The path followed by the front of the tractor was up to 2.0 m less in width when the lazy axle was retracted off the ground.

After the trial, discussions were held with the drivers and operators regarding clearances or tolerances needed between the "tracking curve" and fixed objects in constrained locations. Two tolerances were suggested:

Clearance for a kerb	0.7 m on both sides
Clearance from a wall	1.4 m on both sides

5.4 Tracking Curves

Following this trial, a set of "tracking curves" at 1:500 and 1:200 scales were produced to cover the following requirements:

Vehicle Types	8.0 m rigid truck; 11.0 m rigid truck; 17.0 m semi-trailer; 20.0 m B-train; 9.34 m midi-bus; 11.3 m city bus; 12.3 m tour coach
Turning Angles	30°; 60°; 90°; 120°; 150°; 180°
Turning Radii (wall to wall)	10.0 m*; 12.5 m; 15.0 m; 25.0 m *Not applicable to tour coach
Complex Turns	3-point turns

At the same time it was recommended that:

- The truck-and-trailer combination be omitted as a class of "design" vehicle because the "tracking curves" of the semi-trailer and B-train were believed to be adequate to cover this vehicle.
- As the differences between the "tracking curves" of the mini-bus and the midi-bus do not exceed 1.0 m in width, the mini-bus should be omitted as a class of "design" vehicle.
- A field trial of a B-train executing a 3-point turn should be undertaken to determine a "tracking curve" because of steering difficulties with the computer simulation.

6. TRIALS TO ESTABLISH CLEARANCES REQUIRED BY HEAVY VEHICLES

6.1 Introduction

The purpose of these trials was to establish desirable tolerances or clearances between "tracking curves" and adjacent obstacles. These tolerances are necessary to accommodate not only a reasonable vehicle-to-obstacle clearance but also to accommodate both variations in driver performance and differences between individual vehicles and the "design" vehicle used for the "tracking curve". The results are covered in the report of the supplementary trials for Stage 2, Project GM/11 (Traffic Planning Consultants Ltd 1988).

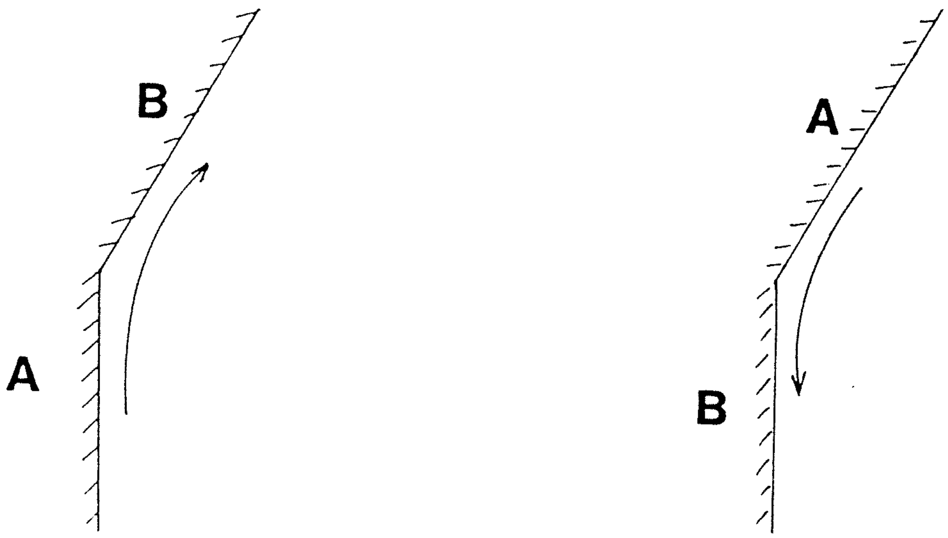
6.2 Procedure

Constrained locations using packing cases were set up, and manoeuvres were carried out (without stops) at speeds appropriate to the every-day situations being simulated.

The constrained locations had two abutting sides, A and B, that were arranged first at 30° and then at 90° angles. Manoeuvres were executed clockwise, then anticlockwise (Fig 6.1), from straight ahead to full lock, and also included complex turns with reversing. The bus performed only the 90° turn.

Vehicles were used that had dimensions close to the "design" vehicles of the large rigid truck, semi-trailer, B-train, and tour coach.

Figure 6.1 Arrangement of sides A and B to simulate constrained locations used to measure clearances required by heavy vehicles for (1) clockwise and (2) anti-clockwise turns.



(1) Clockwise turns

(2) Anti-clockwise turns

6.3 Results

6.3.1 Simple Turns

Clearances derived from measurements of simple turns carried out in the field trials are summarised in Table 6.1. (The arrangement of Side A and Side B is shown in Figure 6.1.)

Table 6.1 Average 85th percentile clearances (metres) for heavy vehicles used in clearance trials.

Manoeuvre	**Clearances (m) for all vehicles**			
	with B-train		**except B-train**	
	Side A	Side B	Side A	Side B
30° Clockwise	0.65	0.73	0.70	0.80
30° Anti-clockwise	0.63	0.66	0.70	0.80
90° Clockwise	0.97	0.98	0.98	0.88
90° Anti-clockwise	0.60	0.72	0.63	0.68

The driver of the B-train manoeuvred significantly closer to obstacles than did drivers of the other vehicles. That the B-train driver had greater experience was no doubt a significant factor in his better estimation of clearance requirements.

The results indicate that:

1. All heavy vehicles making major turns clockwise require greater clearances than for turns made anticlockwise.

2. Except for the 90° clockwise turn, the following clearances should apply:
   0.7 m to wall on approach to turn,
   0.8 m to wall on departure from turn.

In the case of the clockwise turn of the semi-trailer, another vehicle was parked close to the "inside" of the turn. It was noticeable that the driver of the semi-trailer reduced his clearance to the outside walls in this situation, the difference being approximately 0.5 m.

The driver of the bus had not used the particular type of vehicle for some months. His clearance requirements were highly variable and the 85th percentile values were in the range of 1.2 to 1.6 m. With greater familiarity of the vehicle, clearances at the lower end of this range should be more appropriate. Also the point was made that bus drivers have more concern about colliding with obstacles than truck drivers, and therefore a larger clearance for buses, compared with trucks, would be appropriate.

6.3.2 Complex Turns

Because time was limited and moving the packing cases was time consuming, the number of layouts tested was limited.

Complex turns were not simulated for the B-train and the recommendation was that reversing is kept to a minimum. In the trial, the B-train required the entire area available to make a complex turn with clearances reduced almost to zero.

The drivers were questioned about the adequacy of the clearances available during the critical stages of the manoeuvre. A summing up of the reactions of drivers was that they do not feel comfortable with clearances less than 0.7 m, and the driver of the bus required a minimum clearance of 0.9 m.

6.4 Conclusion

Clearances allowed by drivers varied from driver to driver, with the type of turn, and on the influence of constraints on the inside of the turn.

Clearances considered most suitable for use in site design of facilities for heavy vehicles were:

All trucks	0.8 m each side
All tour coaches	0.9 m each side

(these clearances may be applicable to city buses as well)

7. TRIALS TO ESTABLISH VARIATIONS IN THE POSITION OF HEAVY VEHICLE REAR AXES

7.1 Introduction

Field trials had already established that, for many trucks and trailers, the effective position of the rear axis about which a truck turns can vary from the theoretical position. The difference was also thought to be affected by the degree and distribution of the load on the vehicle. When the rear axis is behind the theoretical position it increases the effective wheelbase of the vehicle, which means that in a turn the width of the "tracking curve" is greater than expected. If this phenomenon was widespread then it could have an effect on the choice of "design" vehicles used for the site design recommendations.

The purpose of the investigation was to measure the position of the effective rear axis on a representative sample of the New Zealand heavy vehicle fleet, and from the analysis to decide whether any modifications should be made to the type or dimensions of the "design" vehicles to be used. The results are covered in the report of an extension to Stage 2, Project GM/11 (Traffic Planning Consultants Ltd 1989a).

7.2 Procedure

All heavy vehicles have to undergo a Certificate of Fitness inspection every six months. Those passing through the Ministry of Transport testing station at Otara during one month in 1988 were requested to perform the turning manoeuvre used to determine the position of the effective rear axis of each unit of a heavy vehicle combination.

The turn was performed without turning the steering wheels to full lock to avoid potential problems with some steering mechanisms that do not obey the Ackerman principle, and to prevent "off-tracking" of trailer units becoming unstable.

7.3 Results

A summary of results of the vehicle axes survey are shown in Table 7.1.

Table 7.1 Summary of results of the vehicle rear axes survey.

Measure	Rigid Trucks		Semi-trailers, B-trains			Trucks & Trailers		Buses
	2-axle	3&4-axles	Tractor	Trailer 1	Trailer 2	Truck	Trailer	
Greatest distance (m) FTRA	0.34	0.55	0.70	1.53	0.36	0.27	0.09	0.29
Greatest distance (m) RTRA	0.19	0.61	0.84	0.63	0.49	0.81	0.81	0.28
No. vehicles RA FTRA	55	18	33	15	1	8	6	14
No. vehicles RA RTRA	16	23	13	18	3	12	13	7
85th percentile distance (m) FTRA	0.25	0.38	0.39	0.52	0.36	0.26	0.06	0.22
85th percentile distance (m) RTRA	0.09	0.44	0.47	0.48	0.49	0.58	0.38	0.21
85th percentile distance (m) entire sample	0.08 RTRA	0.30 RTRA	0.18 RTRA	0.42 RTRA	0.14 RTRA	0.32 RTRA	0.37 RTRA	0.21 RTRA

RA	Rear axis
FTRA	Forward of theoretical rear axis
RTRA	Rear of theoretical rear axis

7.3.1 Two-axle Rigid Trucks

The effective rear axis (ERA) of 77% of 2-axle rigid trucks that were surveyed was forward of the theoretical rear axis (TRA). Therefore the "off-tracking" of these trucks would be less than that obtained by simulation. Of the 23% of trucks with ERA behind the TRA, only one showed a difference greater than 0.1 m.

The 85th percentile difference of +0.08 m meant that the effective wheelbase would increase from 5.0 m to 5.08 m. On a 10.0 m radius "tracking curve" this would increase the "off-tracking" by not more than 0.05 m.

The overall effect was insignificant and therefore the dimensions of the 2-axle rigid truck "design" vehicle as originally defined were considered acceptable for the project.

7.3.2 Three- and Four-Axle Rigid Trucks

Considerable differences between ERA and TRA were measured and gave a range of 1.16 m. The 85th percentile difference of 0.30 m (behind) meant the wheelbase of the "design" large rigid truck would increase from 6.5 m to 6.8 m. The increase in "off-tracking" of the effective vehicle from the theoretical vehicle would be no more than 0.3 m on a 10.0 m radius turn.

This was relatively small and the dimensions of the large rigid truck "design" vehicle that were originally defined were considered acceptable.

7.3.3 Two-axle Buses

The ERA of these buses was very small being, at the 85th percentile, 0.09 m behind the TRA. This was insignificant and the dimensions of the two-axle bus "design" vehicles as originally defined were considered acceptable.

7.3.4 Three-axle Tour Coaches

The 85th percentile ERA of tour coaches was 0.21 m behind the TRA. The "off-tracking" would increase by no more than 0.13 m for a "tracking curve" of 12.5 m radius. Therefore the dimensions of the tour coach "design" vehicle as originally defined were considered acceptable.

7.3.5 Semi-trailers and B-trains

The semi-trailer and B-train results were grouped for the analysis. The 85th percentile differences between the TRA and ERA for all components of the vehicles were tractor 0.18 m behind, first trailer 0.42 m behind, and second trailer 0.14 m behind.

The effect of "off-tracking" of the complete vehicle, rather than its components, were considered. If the measured 85th percentile difference between ERA and TRA was applied to the semi-trailer, the wheelbase of the tractor would increase from 4.35 m to 4.53 m, and of a trailer from 8.5 m to 8.92 m. The overall increase in the "off-tracking" of the vehicle would be 0.75 m at a 12.5 m radius.

Because of the significance of this increase in "off-tracking", simulations were made varying the tractor wheelbase only, the trailer wheelbase only, and both together. The increases were 0.2 m, 0.6 m, and 0.85 m respectively at 10.0 m radius. This test showed that the greatest impact on total "off-tracking" occurred when the trailer wheelbase was increased.

As the extra "off-tracking" measured in the tests was significant, it was recommended that the wheelbase of the trailer component of the semi-trailer "design" vehicle be increased by 0.4 m.

7.3.6 B-trains

As the sample was too small, a statistical analysis was not made. Trailer 1 had an ERA forward of the TRA by 0.37 m and Trailer 2 had an ERA that was 0.08 m behind the TRA.

The overall "off-tracking" of the combinations was increased by less than 0.27 m at 12.5 m radius, which was not large. Therefore the dimensions of the B-train "design" vehicle as originally defined were considered acceptable.

7.3.7 Truck and Trailer

The ERA of the truck (first vehicle) was 0.32 m behind the TRA at the 85th percentile. For trailers, the ERA was 0.37 m behind the TRA.

Applying these differences to the "design" vehicle truck and trailer, the overall "off-tracking" would increase by not more than 0.55 m at 12.5 m radius. This was considered to be significant. However the swept path was still within that of the modified semi-trailer "design" vehicle and it was recommended that this be used for the truck and trailer.

7.4 Conclusions

The differences between the ERA and TRA varied considerably with some exceeding 1.5 m. Variations were identified for each unit of a vehicle combination and the effect of these variations on the overall "off-tracking" of the combinations were calculated.

These showed that the dimensions of the medium rigid truck, large rigid truck, city bus and tour coach "design" vehicles as originally defined were appropriate and did not need to be modified.

The dimensions of the wheelbase of the semi-trailer "design" vehicle however did need to be increased by 0.4 m although this would then exceed the legal length. Therefore a revised set of "tracking curves" had to be prepared using the modified semi-trailer "design" vehicle. No recommendations were made concerning the B-train "design" vehicle as the sample was too small.

The dimensions of the truck and trailer "design" vehicle also needed modification. However this modification was not required because the modified semi-trailer "tracking curve" was recommended for use with the truck and trailer.

8. TRIALS TO DETERMINE THE EFFECT OF LOADING ON A HEAVY VEHICLE'S REAR AXIS

8.1 Introduction

The trials to establish the positions of both the effective and theoretical heavy vehicle rear axes (ERA, TRA respectively), indicated that a load and its position on the vehicle affects its "tracking curves". Thus the survey of ERA and TRA of heavy vehicles was extended to obtain the appropriate information.

The purpose of these trials was to investigate the effects that the size and position of a load on a truck have on the position of a vehicle's rear axis. The results are covered in the report of a second extension to Stage 2, Project GM/11 (Traffic Planning Consultants Ltd 1989b).

Generally heavy vehicles arrive at the facility site either laden or unladen and depart in an unladen or laden state. Therefore the assessment of any differences in positions of ERA may be significant in designing facilities, because the space required for a turn may be different. If so, revision of the "tracking curves" may be required to accommodate laden and unladen "design" vehicles.

8.2 Procedure

The trials were carried out on a flat dry sealed surface free of loose chips. The weighing was carried out on electronic measuring unit (EMU) equipment by Ministry of Transport personnel. Tests of the accuracy of the equipment were made by taking three successive weighings of a vehicle of known tare weight and load.

Two rigid trucks and two semi-trailer combinations were used. The same trailer was used with each of the two tractors. One of the rigid trucks had single axle drive and torque reactive suspension, and the second truck had tandem drive.

The loading materials were palletised paving slabs, each pallet weighing approximately 1.33 tonnes. Four load configurations were used:

1. empty;
2. half load on front half of deck;
3. half load on rear half of deck;
4. full load.

8.3 Results

The results of the loading trials are shown in Table 8.1.

Table 8.1 Differences between TRA and ERA for different loadings.

Vehicle	Empty	Half load: (fore)	Half load: (rear)	Full
6x4 rigid truck	F 0.02	F 0.01	R 0.06	R 0.02
6x2 rigid truck	F 0.24	F 0.34	F 0.05	F 0.24
Semi-trailer 6x4:				
tractor	F 0.32	F 0.51	F 0.56	F 0.58
trailer	R 0.36	R 0.17	R 0.28	R 0.13
Semi-trailer 6x2:				
tractor	R 0.33	x	x	x
trailer	R 0.12	x	x	x

F ERA forward of TRA
R ERA rear of TRA

8.4 Discussion

8.4.1 6x4 Rigid Truck

Differences between ERA and TRA were small. The rear half-load had the most effect on "off-tracking".

8.4.2 6x2 Rigid Truck

This truck had torque reactive suspension. Differences between ERA and TRA were greater than for the 6x4 truck. The ERA was always forward of the TRA and the vehicle will require less tracking width than the "design" vehicle. Again, rear loading had the most effect on "off-tracking".

8.4.3 6x4 Semi-trailer

The trailer unit had an ERA that was always behind its TRA, and when empty had the most effect on "off-tracking" (being 0.36 m behind) and least effect when fully laden (being 0.13 m behind). The tractor had a similar ERA when fully loaded, or with front or rear half loads, being 0.51 m to 0.58 m forward.

Flexing of the trailer's structural frame occurs when the load is forward of the rear axle group and will most likely cause increased load on the front axle and decreased load on rear axle. Therefore the rear axle group is likely to scuff, and ERA of the trailer will shift forward compared with the unladen situation.

"Off-tracking" requirements were always less than simulated calculations. For the unladen case, the "off-tracking" was 0.02 m less on a 15.0 m radius than the simulation with a TRA.

8.4.4 6x2 Semi-trailer

Only the unladen result was available. This was the same trailer that was used with the 6x4 tractor but the ERA had moved from 0.36 m behind to 0.12 m behind.

Overall weight supported by the trailer's triple axle group was unchanged although the distribution of weight to each axle had changed and was measured.

8.5 Conclusions

Field trials showed that a load and especially its position influenced the position of the ERA of a heavy truck.

Rigid trucks required more space to allow for "off-tracking" when the load was over the rear half of the vehicle's deck. This commonly occurs in practice. However the difference between "off-tracking" of the "design" vehicle and of the trial vehicle was not great.

The ERA of unladen semi-trailers was the furthest back, and therefore increased space was required to allow for "off-tracking" compared with the fully or partially laden trailer. However, the difference between "off-tracking" of the "design" vehicle and of the trial vehicle was not great.

The effects of loading on the position of the rear axis of a heavy vehicle can be significant but did not warrant changes to the "design" vehicles and their "tracking curves" that had already been adopted.

9. GLOSSARY

Dynamic equilibrium

State obtained when "off-tracking" has been stabilised by continuous rotation.

Tail swing

Penetration of the rear of the vehicle outside the "normal" envelope of its swept path.

Torque reactive suspension

When a vehicle accelerates, torque reactive suspension (TRS) operates so that weight increases on the forward-most axle in the rear axle group, and decreases on the rearmost axle, with a resulting increase on the driving axle. The coefficient of friction increases which gives better acceleration.

When a vehicle decelerates when braking, weight increases on rear-most axle of the rear axle group, in part offsetting the forward-biased axle weight redistribution that occurs during braking, and increasing the stopping capability of the vehicle.

Overall TRS varies the individual axle weights in that suspension group. It affects the coefficient of friction between tyres and pavement but scuffing is more likely to occur.

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