Comparison of Simulation and Test Results for Various Truck Combination Configurations

C.P. Lam[1]

ABSTRACT

The Ontario Ministry of Transportation and Communications conducted tests of nine truck combinations with one, two, or three trailers in either A-, B-, or C-train configuration under the auspices of the CCMTA/RTAC Vehicle Weights and Dimensions Study. These tests provided a wealth of data on the vehicle response in a variety of manoeuvres over a wide speed range.

Computer simulations, using the actual measured steer input, were conducted with the UMTRI yaw/roll non-linear vehicle dynamics simulation program. This work necessitated improvements to both the capability and efficiency of the yaw/roll program. Input data sets were prepared to represent the actual test vehicles. The physical dimensions and mass properties of the test vehicles were measured, and generic suspension and tire properties were selected from UMTRI's laboratory measurements performed on behalf of the Vehicle Weights and Dimensions Study.

This paper summarizes the modifications made to the yaw/roll program and comparisons between simulation and test responses of the nine vehicles.

1. INTRODUCTION

The effects of weight and dimension parameters on heavy truck stability and control and on pavement response was examined in the CCMTA/RTAC Vehicle Weights and Dimensions Study. The objective of the study was to compile technical information that, with an earlier study of the effects of heavy trucks on bridge loading (1), would provide a basis for the provinces to amend their truck weight and dimension regulations. The goal was to simplify interprovincial trucking through greater uniformity in these regulations.

The truck population of Canada was surveyed (2), and six generic families were defined, based on the number of trailers and hitching methods. One vehicle in common use in at least some provinces was selected as representative of each family and designated as the baseline vehicle configuration. Each baseline vehicle served as a yardstick against which variations in weight, dimension, or equipment were to be evaluated by means of a comprehensive series of computer simulations. The Ontario Ministry of Transportation and Communications (MTC) was asked to test the six baseline vehicles plus three tractor-trailer combinations and compare the results with the computer simulation of the tested vehicles as part of its contribution to the study.

Test results are presented in References 3 to 12. This paper deals with the computer simulation aspect of the tested vehicles, using the University of Michigan Transportation Research Institute's (UMTRI's) yaw/roll program.

The main objective was to conduct computer simulations using the measured test inputs and actual vehicle unit properties, to demonstrate that simulation can represent vehicle responses for a wide range of vehicles and test manoeuvres.

A secondary objective was to demonstrate that a comprehensive simulation program, if properly modified, can be run in a mini-computer at a reasonable execution speed.

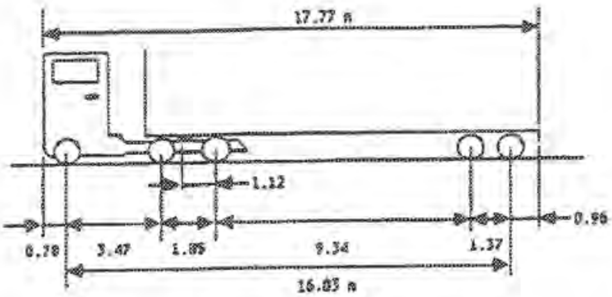
This paper summarizes the modifications made to the UMTRI yaw/roll program and the comparative study between computer simulation and test responses of the nine vehicles.

2. TEST VEHICLES

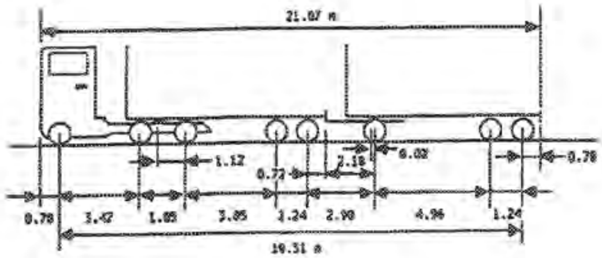
The set of vehicles was defined and provided to MTC by the study. Nine configurations were selected from the generic families:

- 45 ft semi

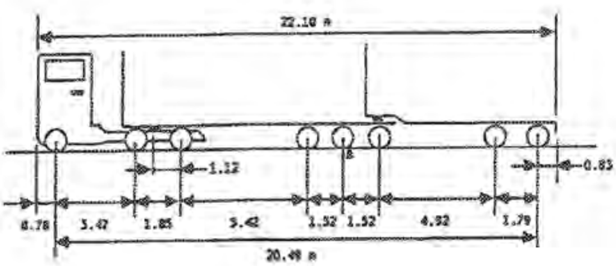
1 Research Officer, Automotive Technology and Systems Office, Transportation Technology and Energy Branch, Ontario Ministry of Transportation and Communications, Downsview



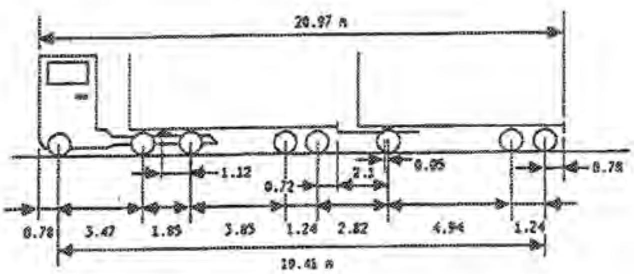
45 ft semi, vehicle dimensions
FIGURE 1a



A-train double, vehicle dimensions
FIGURE 1b



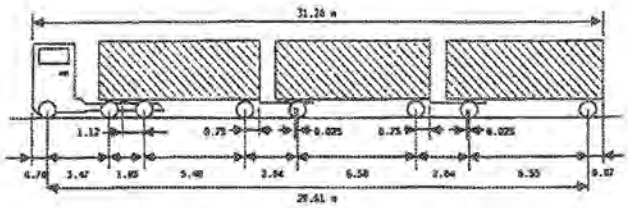
B-train double, vehicle dimensions
FIGURE 1c



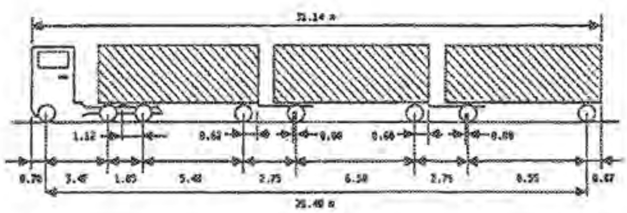
C-train double, vehicle dimensions
FIGURE 1d

- 5-axle 48 ft semi
- 6-axle 48 ft semi
- 7-axle 48 ft semi
- A-train double
- B-train double
- C-train double
- A-train triple
- C-train triple

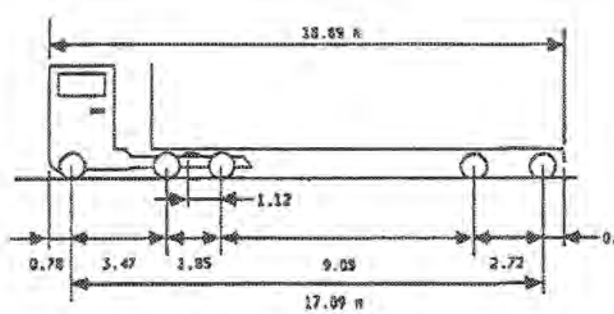
Each test vehicle consisted of the MTC Freightliner as the prime mover and the trailer or trailer combination being tested. Except for the triple combinations which had van-type trailers with a single



A-train triple, vehicle dimensions
FIGURE 1e

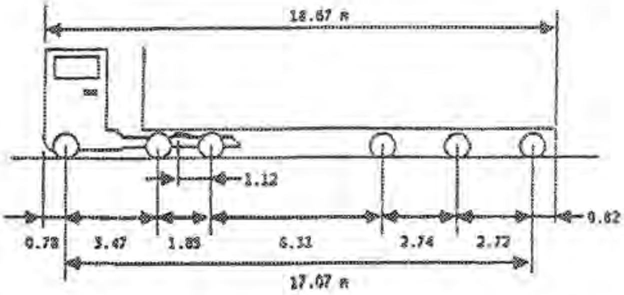


C-train triple, vehicle dimensions
FIGURE 1f



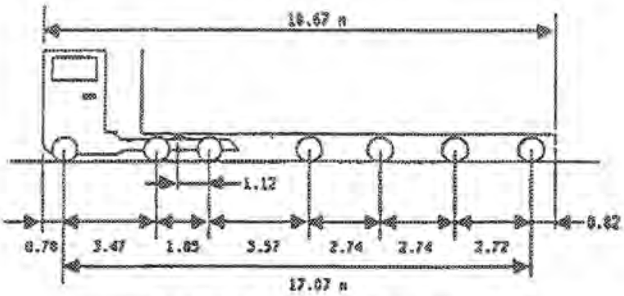
5-axle 48 ft semi, vehicle dimensions
FIGURE 1g

binations which had van-type trailers with a single axle supported by a single-leaf spring suspension, all other configurations employed flatbed trailers with a tandem or triple axle supported by multi-leaf spring suspensions with torque rods and equalizer arms. In the case of the 6- and 7-axle 48 ft (14.63 m) semi, additional axles were supported by air suspensions. Each converter dolly had a single axle supported by leaf spring suspensions. Detail descriptions of the individual vehicle units can be found in Reference 14. Figure 1 gives the dimensions of all the vehicles being examined. Physical properties of the various vehicle units are shown in Table 1. The Freightliner front axle used Michelin XZA radial tires, size 11R24.5, load range G, and the drive axles used Michelin XM+S4 radial tires, load range G, size 11R24.5.



6-axle 48 ft semi, vehicle dimensions

FIGURE 1h



7-axle 48-ft semi, vehicle dimensions

FIGURE 1i

Table 1 – Physical properties of the various vehicle units

Vehicle unit	Sprung mass kg (lb)	C.G. height m (in)	Inertia Nm sec2 (lb in sec2) I_{xx}	I_{yy}	I_{zz}
MTC Freightliner	6 124 (13 500)	1.13 (44.5)	2 600 (23 000)	22 030 (195 000)	28 245 (250 000)
45 ft Semi	19 605 (43 222)	1.69 (66.5)	22 088 (195 500)	420 490 (3 721 850)	434 218 (3 843 345)
5-axle 48 ft semi	21 244 (46 834)	1.58 (62.3)	22 044 (195 116)	500 000 (4 426 300)	510 580 (4 519 200)
6-axle 48 ft semi	27 950 (61 614)	1.74 (68.5)	26 375 (233 450)	502 880 (4 451 100)	515 430 (4 562 170)
7-axle 48 ft semi	33 980 (74 914)	1.76 (69.1)	27 250 (241 183)	567 560 (5 023 560)	581 920 (5 150 671)
B-train lead trailer	16 960 (37 390)	1.68 (66.0)	18 770 (166 130)	161 285 (1 427 560)	171 579 (1 518 680)
B-train rear trailer	18 100 (39 900)	1.73 (68.0)	18 940 (167 630)	113 594 (1 005 444)	123 820 (1 095 940)
A- or C-train double trailer	15 920 (35 100)	1.66 (66.5)	17 963 (159 000)	110 327 (976 530)	120 916 (1 070 250)
A-train double dolly	790 (1 740)	0.86 (34.0)	190 1 684)	435 (3 855)	551 (4 883)
C-train dolly	680 (1 500)	0.90 (35.6)	120 (1 055)	407 (3 600)	477 (4 225)
A-train triple dolly	610 (1 345)	0.90 35.6)	106 (940)	355 (3 145)	415 (3 670)
A- or C-train triple trailer	13 517 (29 800)	1.64 (64.5)	21 353 (189 000)	101 680 (900 000)	106 935 (946 500)

Michelin XZA radial tires, size 11R22.5, load range H, were used on all trailer and dolly units. Concrete blocks were used to load the trailer unit to achieve axle loads specified by the study. Table 2 shows the axle loads of the nine configurations. Outriggers were installed on each trailer to limit the roll angle to about 7°, and safety cables were installed to limit the articulation between units as safety measures to minimize damage to the vehicles.

3. SIMULATION PROGRAM

3.1 YAW/ROLL MODEL

The yaw/roll model is one of the simulation programs developed at UMTRI to study the directional and roll response of multi-articulated commercial vehicles in the time domain (15). The model was designed to simulate a general truck-train combination of up to four vehicle units, with a total of 11 axles distributed in any arbitrary configuration, except with a single tractor front axle. The vehicle model was developed based on the following assumptions:

- Each vehicle unit consists of a rigid body sprung mass and a number of beam axles as unsprung masses connected to the sprung mass through compliant suspensions.
- The vehicle is moving at a constant forward speed on a horizontal surface with a uniform frictional characteristic.
- Each sprung mass has five degrees of freedom in the lateral, vertical, roll, pitch, and yaw directions, whereas each unsprung mass is capable only of roll and bounce with respect to the sprung mass.
- Pitch motion of the vehicle is assumed to be small, such that sin $(\phi_s - \phi_u)$ and cos $(\phi_s - \phi_u)$ can be approximated by $\phi_s - \phi_u$ and 1, respectively.
- The relative roll displacement between the sprung mass and the unsprung mass is small, such that sin and cos are approximated by respectively.
- The forces between the sprung mass and the unsprung mass are assumed to be transmitted through the roll centre of each axle, located directly underneath the sprung mass and free to move in the vertical axis of the unsprung mass.

Table 2 – Axle load of various configurations

Vehicle type	Axle load kg (lb) 1	2	3	4	5	6	7	8
45 ft semi	5 118 (11 260)	6 114 (13 450)	6 114 (13 450)	6 882 (15 140)	6 977 (15 350)			
A-train double	5 127 (11 280)	5 327 (11 720)	5 486 (12 070)	5 250 (11 550)	6 882 (15 140)	7 400 16 280)	6 936 (15 260)	5 291 (11 640)
B-train double	4 991 (10 980)	6 082 (13 380)	5 723 (12 590)	7 864 (17 300)	7 827 (17 220)	7 232 (15 910)	7 536 (16 580)	5 509 (12 120)
C-train double	5 127 (11 280)	5 445 (11 980)	5 464 (12 020)	5 664 (12 460)	6 536 (14 380)	7 727 (17 000)	6 814 (14 990)	5891 (12 960)
A-train triple	5 286 (11 630)	5 914 (13 010)	5 168 (11 370)	7 800 (17 160)	8 073 (17 760)	7 964 (17 520)	8 005 (17 610)	7 732 (17 010)
C-train triple	5 286 (11 630)	5 914 (13 010)	5 168 (11 370)	7 800 (17 160)	8 295 (18 250)	7 964 (17 520)	8 227 (18 100)	7 732 (17 010)
5-axle 48 ft semi	5 055 (11 120)	7 336 (16 120)	6 827 (15 020)	7 618 (16 7600)	7 573 (16 660)			
6-axle 48 ft semi	5 373 (11 820)	7 505 (16 510)	6809 (14 980)	7 396 (16 270)	7 714 (16 970)	6 746 (14 840)		
7-axle 48 ft semi	5 255 (11 560)	7 923 (17 430)	7 232 (15 910)	7 464 (16 420)	8 177 (17 990)	6 577 (14 470)	7 250 (15 950)	

- Each suspension is independent of other suspensions, such that inter-axle load transfer of load-sharing suspensions is neglected.

- The principal axes of inertia of the sprung and unsprung masses coincide with their respective body-fixed co-ordinate system.

- Sprung masses are connected by one of four hitch mechanisms: pintle hook, kingpin, fifth wheel, or inverted fifth wheel. With the pintle hook mechanism, the trailing unit is capable of bounce, roll, yaw, and pitch with respect to the lead unit. The kingpin connection allows only yaw motions between the leading and trailing units. Both the fifth wheel and inverted fifth wheel allow each unit to roll, pitch, and yaw with respect to one another.

Details of the mathematics of the equations of motion can be found in Reference 15.

State-of-the-art simulation techniques were implemented in the model, and the following special features were included in the yaw/roll program:

- non-linear tire characteristics of the tire-road interface in the form of cornering force and aligning moment as a function of slip angle and vertical axle load by lookup tables;

- non-linear suspension characteristics in the form of load versus deflection by lookup tables;

- simulation in either the open-loop mode using steer angle input or the closed-loop mode using a predefined vehicle trajectory as input data;

- self-steering axle and B-dolly configuration;

- four types of hitch mechanism: pintle hook, kingpin, conventional fifth wheel, and inverted fifth wheel.

With these features, the most complex configuration that can be simulated is a C-train double with a steerable axle at the B-dolly.

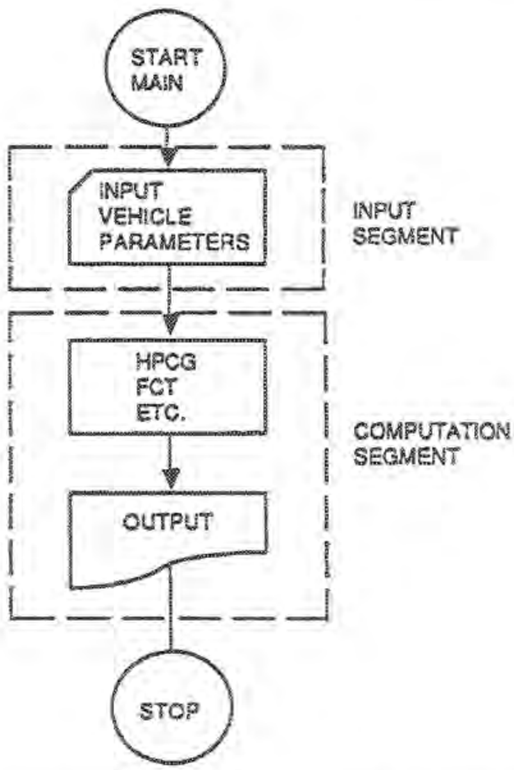
3.2 MODIFICATION

Figure 2 shows a simplified flowchart of the UMTRI yaw/roll program, which consists of a main program and a number of subroutines within one program code. The original program operated on IBM mainframe equipment. To install the yaw/roll program on a modest minicomputer such as the HP-1000 A700 used by MTC for test data acquisition and processing, a substantial amount of modification was required to reduce program size and obtain a reasonable execution speed. The modifications made to the original yaw/roll program can be divided into four different areas, namely, I/O structure, program size reduction, computation changes, and program augmentation.

3.2.1 I/O Structure

The new program has a fixed field input format for all parameters so that the input data set is readable. The input data set was split into two, one for the vehicle parameters and the other for the vehicle operating conditions. The purpose of this new arrangement was to facilitate simulation of test runs by defining the operating conditions of the vehicle in a separate file.

The output section of the yaw/roll program was completely restructured. Instead of printing all the simulation responses, the user now defines exactly which parameters are required, and the responses are stored in a file with the same format as the test data. Thus, simulation and test responses can



UMTRI yaw/roll program, simplified flowchart

FIGURE 2

be compared readily. The output of the simulation has been converted to metric units.

3.2.2 Program Size Reduction

The following steps were taken to reduce the core requirement of the yaw/roll program:

- Similar subroutines, such as FORTAB and ALTAB, were combined through code generalization.
- The closed-loop driver model, together with the supporting subroutines, was deleted from the program.
- Irrelevant subroutines and variables were deleted.
- The number of tire types allowed was reduced from 11 to 2.
- The output array dimensions were reduced from (18,14,45) to (18,14) by virtue of the I/O structural change.
- Program code was simplified to eliminate some variable arrays.
- Dimensions of the matrices were redefined to store only non-zero partitions.

As a result of all these changes, the size of the yaw/roll program was greatly reduced so that it could fit the limited memory of the HP-1000.

3.2.3 Computation Coding

The changes described in this section were responsible for the improvement in execution speed of the yaw/roll program. The program code was simplified to minimize the number of computer operations because the FORTRAN compiler did not provide object code optimization. This reduced execution time and program size. The matrix arithmetic was modified to include only the non-zero calculations. Again, this reduced both size and execution time of the program. The hardware vector instructions of the HP-1000 A700 were also used throughout the computation, where appropriate. A search subroutine was added to "remember" the current index for the non-linear table lookups to minimize the amount of searching.

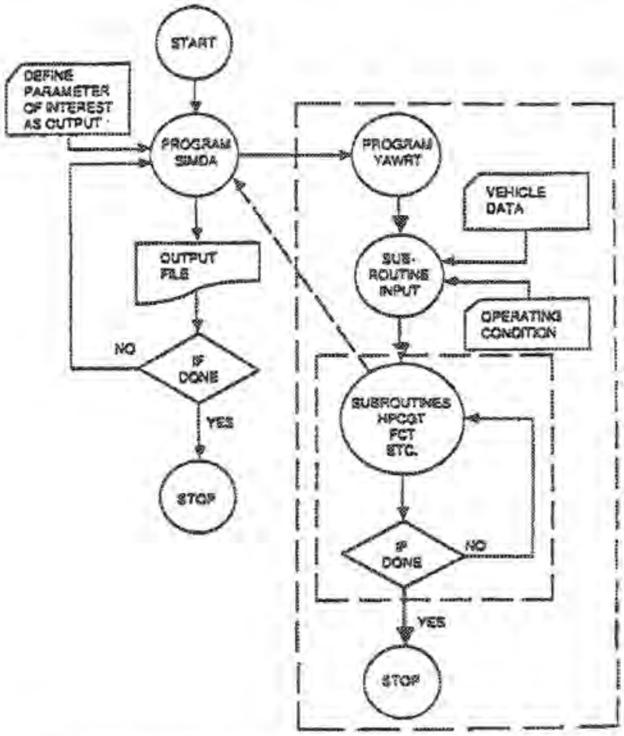
3.2.4 Program Augmentation

Because of the changes made in the matrix computation, the program could be extended to allow simulation of an A-train triple combination, which has six sprung masses, without requiring a large increase in memory. Additional features such as a twin-steer front axle had previously been implemented. The pintle hook representation was modified to include a vertical constraint so that it was more representative of the actual physical system. A subroutine was included to convert lateral acceleration from the unit's centre of mass to any other location to facilitate comparison between test and simulation results.

With the latest improved version of the B-dolly model developed at UMTRI, the MTC version of the yaw/roll program could now be used to simulate a C-train triple with steerable axles.

3.2.5 MTC Yaw/Roll Program

Figure 3 shows the simplified flowchart of the improved yaw/roll program. Simulation is initiated by program SIMDA, which, in turn, starts program YAWRT and then waits for the simulation results. Program YAWRT has a similar function to the original yaw/roll program in that it reads in all the vehicle parameters and operating conditions by subroutine INPOT and performs the integration by HPCGT. However, upon completion of each time step, results of the simulation are sent to program SIMDA, which then puts the result into the appropriate array for eventual storage in a file on disk.



MTC yaw/roll program, simplified flowchart

FIGURE 3

3.3 DATA SOURCE

Two types of data are required as input to the simulation model: the vehicle parameters and the operating parameters. The vehicle parameters can further be separated into two groups: the physical properties and dimensions of the vehicle; and the mechanical properties of the suspension system, the tire-road interface, and the steering characteristics of the B-dolly self-steering axle.

As far as the vehicle parameters are concerned, all dimensions were measured from the vehicle on the test track.

Axle loads were obtained by a portable scale placed directly underneath the tires. Mass properties were estimated from the structural components and accessories of the vehicle unit, including the payloads.

The mechanical properties of the suspension system and the tire characteristics were taken from laboratory measurements performed by UMTRI on behalf of the Vehicle Weights and Dimensions Study (16). The suspension compliance was represented by a non-linear force deflection table, whereas the tire characteristics were represented by non-linear cornering force and aligning torque as a function of sideslip and axle load, also in the form of lookup tables. The B-dolly axle steering characteristics were represented by a torque steer table.

The vehicle operating parameters were chosen directly from the processed test data. The steer angle input was picked from the test data at a fixed time step, typically 0.1 s. The forward speed was determined as the average speed of the vehicle over a period of 1 s, immediately before the start of the steer input. The initial yaw angle and yaw rate of the tractor were taken directly from the test data at the start of the steer input. Other initial conditions were assumed to be zero.

4. SIMULATION RESULTS

Computer simulations were conducted for each of the nine vehicles in sinusoidal steer, lane change, and steady circular turn manoeuvres over a wide range of operating conditions. Due to the scope of this paper, it is not possible to present the simulation results of all nine vehicles in each of the three manoeuvres. However, effort has been made to include at least one configuration from each generic family to demonstrate the effectiveness of computer simulation in the prediction of the directional and roll responses in either one of the three manoeuvres. Additional simulation results can be found in Reference 14. Due to lack of measured data for the steering properties of the Sauer's axle used on the B-dollies, the laboratory-measured steering characteristics of a Ceschi axle, which was considered closest to the Sauer's axle, from UMTRI's data bank were used in the simulation of all C-train configurations.

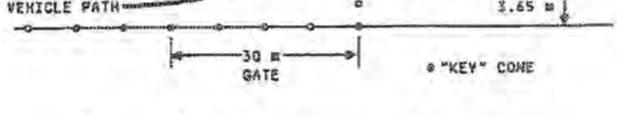
4.1 LANE CHANGE

The lane change on a standard highway requires a steer input similar to the sinusoidal steer. The amplitude of the steer input must be such that a sidestep of 3.66 m (12 ft) is achieved if the vehicle starts in the centre of one lane and moves over to the centre of an adjacent lane. This test is representative of an obstacle avoidance manoeuvre on a multilane highway, where the sudden appearance of an obstacle necessitates a fast lane change to the left.

The test course was laid out on a high-friction surface, as shown in Figure 4. The 30 m (98 ft) gate was selected so that speeds at the limits of stability for all vehicles would be in the range of 70 to 90 km/h. The vehicle was loaded, and the driver approached the course at constant speed. The driver's task was to manoeuvre the vehicle through the gate while maintaining speed, without loss of control or contact of any of the cones by the vehicle. A sequence of runs was conducted at increasing speeds until the vehicle became unstable by rollover or there was an unacceptable trailer swing out of lane, defined here as in excess of 1 m. The test was terminated at 100 km/h, even if the vehicle was still able to complete the manoeuvre successfully.

4.1.1 45 ft Semi

Computer simulation was conducted for the 45 ft (13.72 m) semi executing the lane change manoeuvre at various speeds ranging from 47 to



Lane change manoeuvre course

FIGURE 4

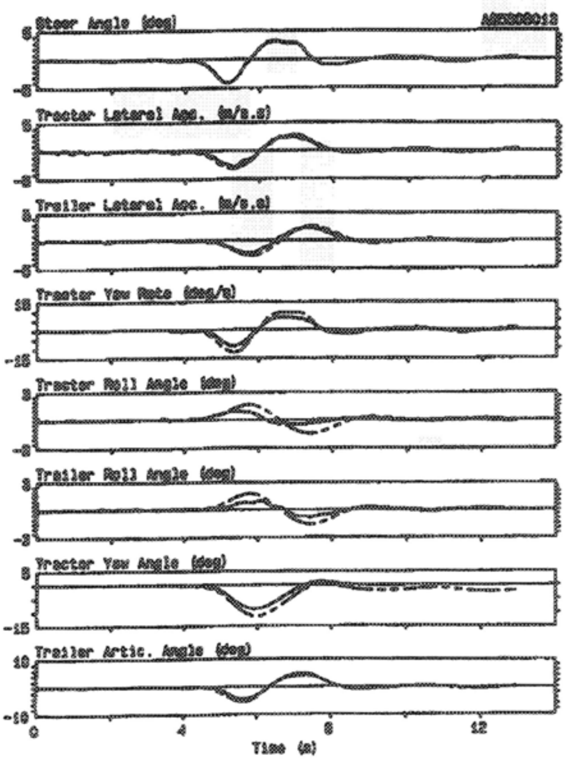
100 km/h. Figure 5 compares the responses of simulation and test at a speed of 72 km/h. In this and subsequent vehicle response figures, dotted lines denote simulation responses and solid lines denote test responses. There is, in general, good agreement in the directional response of the vehicle units, even though there are some small differences between the peak responses of lateral acceleration of both the tractor and trailer. The roll angle responses of the tractor and trailer predicted by the simulation are slightly higher than the test responses, but the amplitudes are too small to be significant and the correlation is good. Similar agreement was found at other speeds.

4.1.2 B-Train Double

The B-train double was simulated for speeds ranging from 47 to 89 km/h. With the "standard" tire characteristics, there was no agreement between simulation and test responses for the three vehicle units. By replacing the tire characteristics at the tractor drive axles with that of a "worn" tire, the simulation agreed well with the test result, as shown in Figure 6. There is excellent agreement in the directional response and fairly good agreement in the roll response of the first and second trailer with the "improved" tire characteristics. Similar agreement was found at other speeds, even though the simulated responses appeared to have a higher damping at the end of the manoeuvre at higher speeds, possibly due to change of tire characteristic at higher speed.

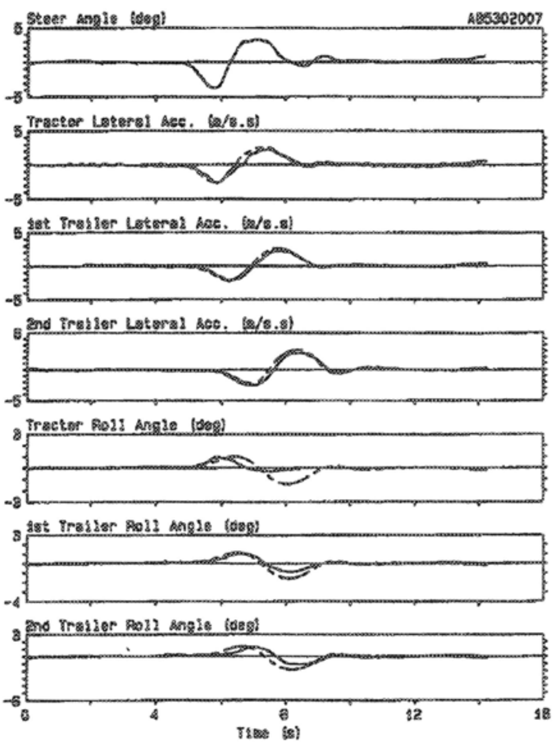
4.1.3 C-Train Double

Figure 7 shows the lane-change response of the C-train double predicted by the simulation superimposed on the test result for a speed of 72 km/h. In this and subsequent simulation of the C-train configurations, the steering characteristics of the Ceschi axle were used for the B-dollies because of a lack of measured data for the steering properties of the Sauer axle. There is excellent agreement in the lateral acceleration response of all vehicle units throughout the manoeuvre. The vehicle showed a significant amount of second trailer swing after the trailer reached the left lane, and the simulation model predicted a similar response. It can be seen that the simulation model produced an excellent prediction of the dolly steer angle throughout the entire lane-change manoeuvre. Similar results were found at higher speeds, although the level of agreement deteriorated at the end of the manoeuvre, possibly due to the change in tire characteristics as a function of speed.



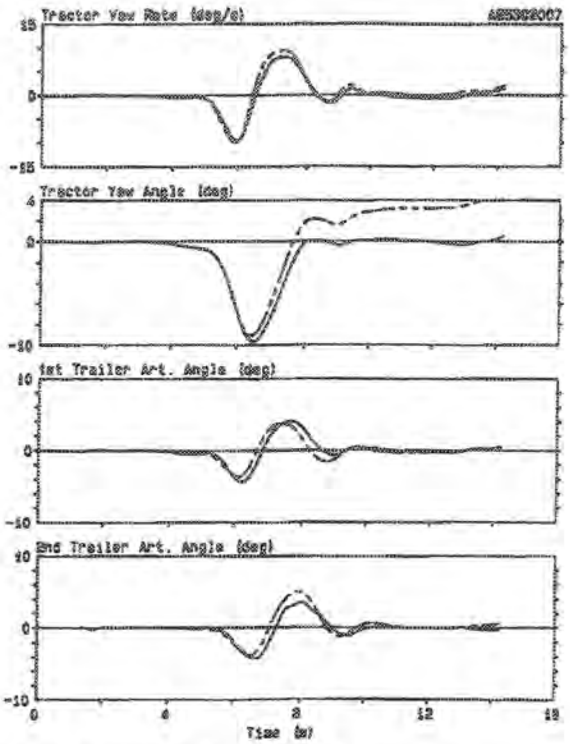
45 ft semi, single lane change responses at 72 km/h

FIGURE 5



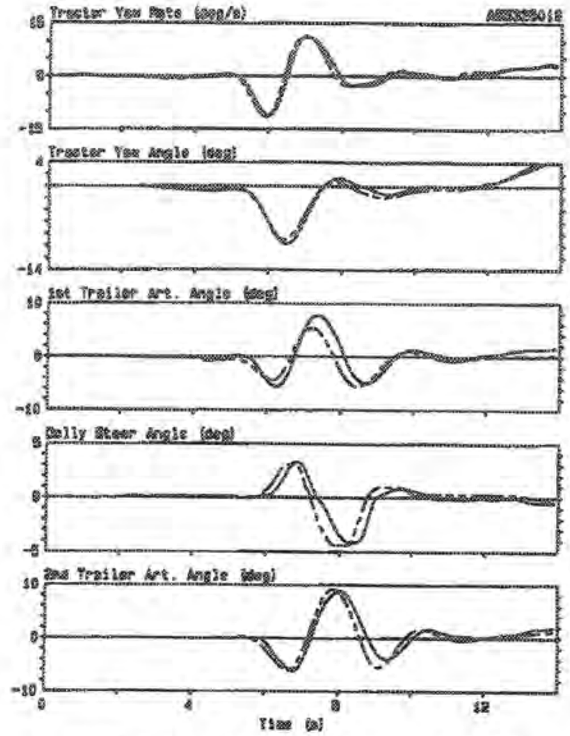
B-train double, single lane change responses at 63 km/h (refined tire characteristics)

FIGURE 6a



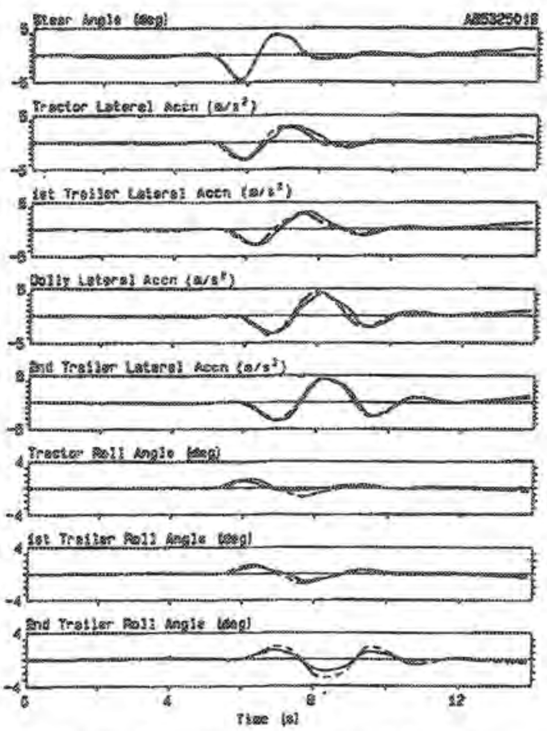
B-train double, single lane change responses at 63 km/h (refined tire characteristics)

FIGURE 6b



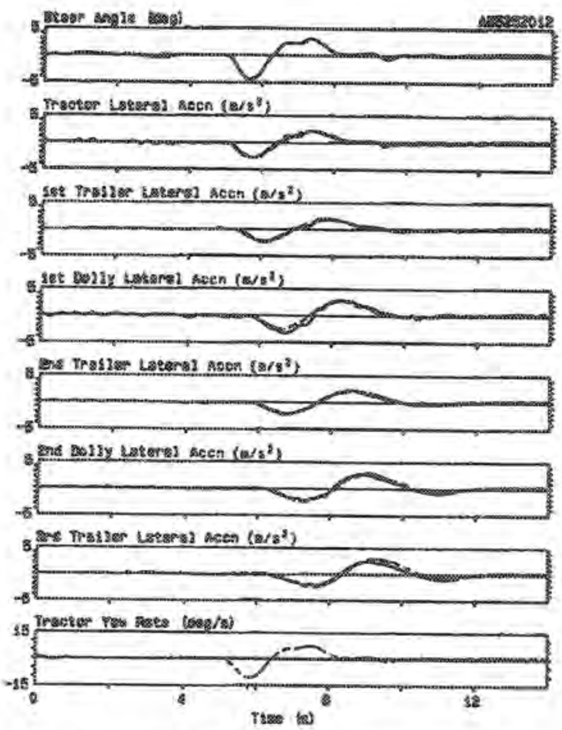
C-train double, single lane change responses at 72 km/h

FIGURE 7b



C-train double, single lane change responses at 72 km/h

FIGURE 7a



C-train triple, single lane change responses at 63 km/h

FIGURE 8a

4.1.4 C-Train Triple

Computer simulation of the lane change manoeuvre for the C-train triple was conducted between speeds of 35 and 89 km/h, at which point the test vehicle response became unacceptable. Figure 8 compares the simulation and test responses at a speed of 63 km/h. There is close agreement in the directional response, and the first dolly steer angle response. While the simulation model predicted a similar steer response at the second dolly, the test data showed a very small steer angle. The difference in peak roll angle response is believed to result from transducer accuracy and the torsional rigidity of the vehicle units. Again, there is a good correlation in the roll angle responses between test and simulation. Similar agreement was found at other speeds.

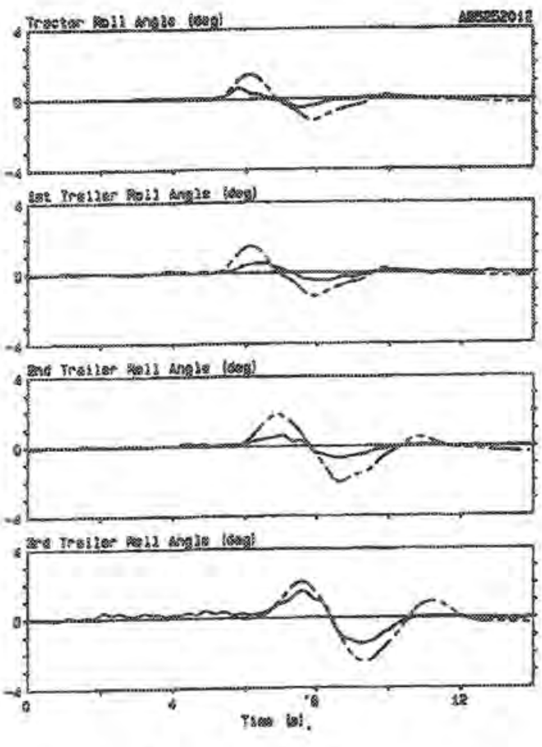
4.1.5 7-Axle 48 ft Semi

The 7-axle 48 ft (14.63 m) semi was tested from 47 to 100 km/h. With this configuration, simulation using the "standard" tire characteristics for all axles did not predict similar response as the test measurement, as shown in Figure 9. By changing the tire characteristics at the tractor drive axles and the third and fourth axle of the trailer with similar tire characteristics as that used for the B-Train double, the simulation responses were made to agree well with the test results. Figure 10 compares the simulation and test responses at a speed of 92 km/h. There is excellent agreement in the directional responses of both the tractor and trailer, and the only parameters that do not have complete agreement are the roll angle responses of the tractor and trailer. However, they are small and there is a good correlation between simulation and test response. Similar agreement was found at other speeds.

4.2 STEADY CIRCULAR TURN

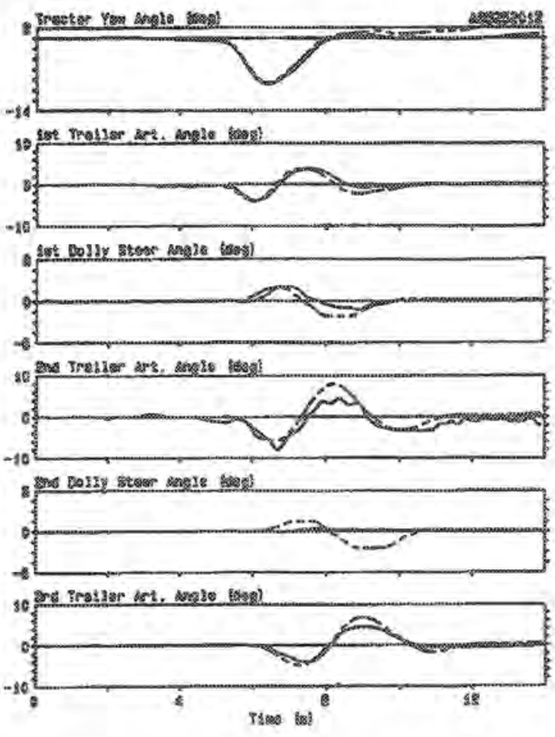
The steady circular turn course was laid out using traffic cones on a dry high-friction surface, as shown in Figure 11. The circle had a radius of 50 m (164 ft), with a 100 m (328 ft) long entry spiral. The vehicle was loaded, and the driver followed the approach at a specified constant speed, entered the circular turn as smoothly as possible, and followed on the outside for 90 to 180, or as long as possible. A sequence of runs was conducted at increasing speeds until the vehicle became unstable by rollover or trailer swing or the driver could not maintain either the desired trajectory or the speed.

It became evident after the simulation of a few vehicle configurations that the tire characteristics



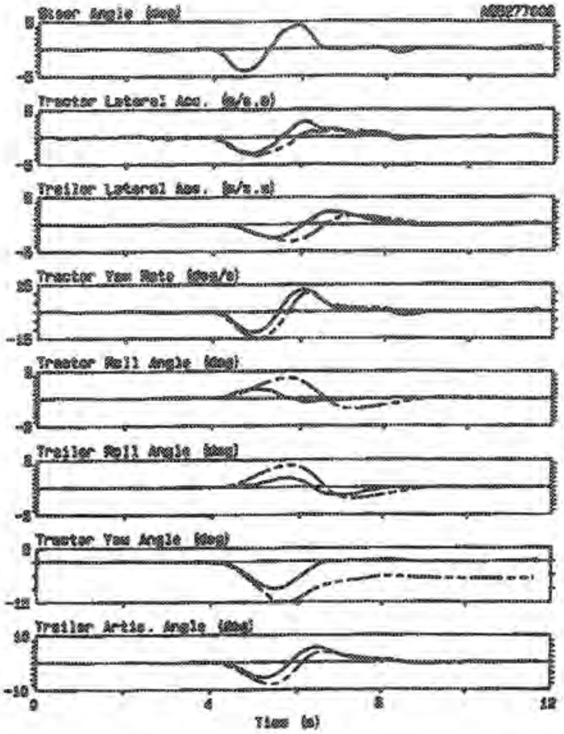
C-train triple, single lane change responses at 63 km/h

FIGURE 8b



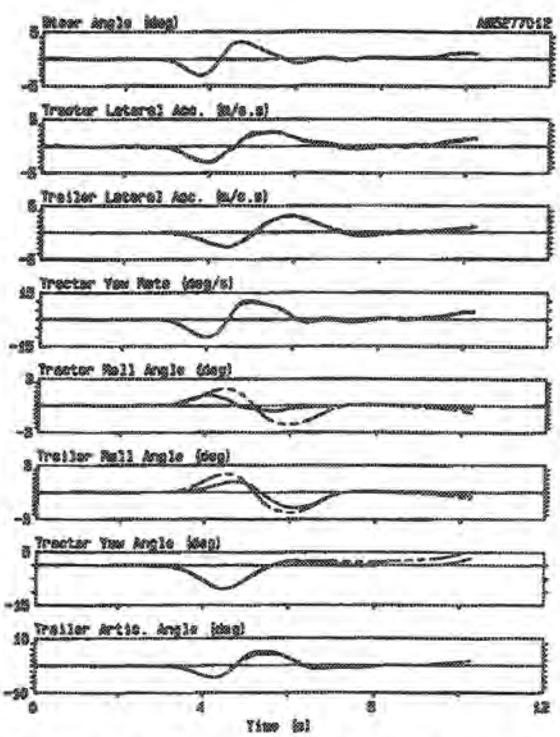
C-train triple, single lane change responses at 63 km/h

FIGURE 8c



7-axle 48 ft semi, single lane change responses at 72 km/h

FIGURE 9



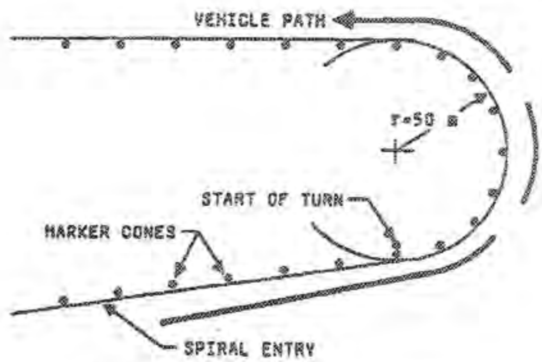
7-axle 48 ft semi, single lane change responses at 92 km/h

FIGURE 10

at the tractor drive axle had to be modified to achieve better agreement in the steady-state response between test and simulation of all the vehicles. The tire characteristics chosen for the drive axle of the tractor were the same as those used for the B-train double and 7-axle 48 ft (14.63 m) semi in the lane change manoeuvre.

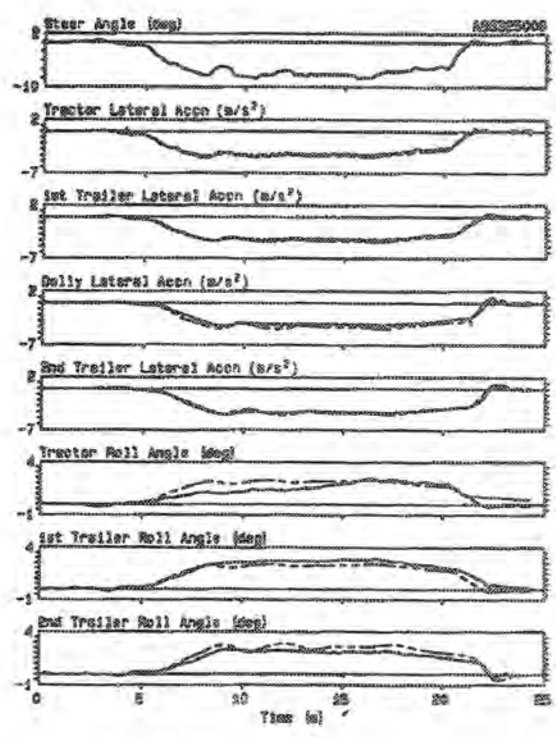
4.2.1 C-Train Double

Figure 12 compares the steady circular turn response of the C-train double between simulation and test at a speed of 55 km/h. Excellent agree-



Steady circular turn course

FIGURE 11



C-train double, steady circular turn responses at 55 km/h

FIGURE 12a

ment is seen for lateral acceleration of all vehicle units, tractor yaw angle, first trailer articulation, and the roll responses. The difference between test and simulation in the dolly steer angle is not known at this stage. Similar agreement between simulation and test responses was found at other speeds.

4.2.2 C-Train Triple

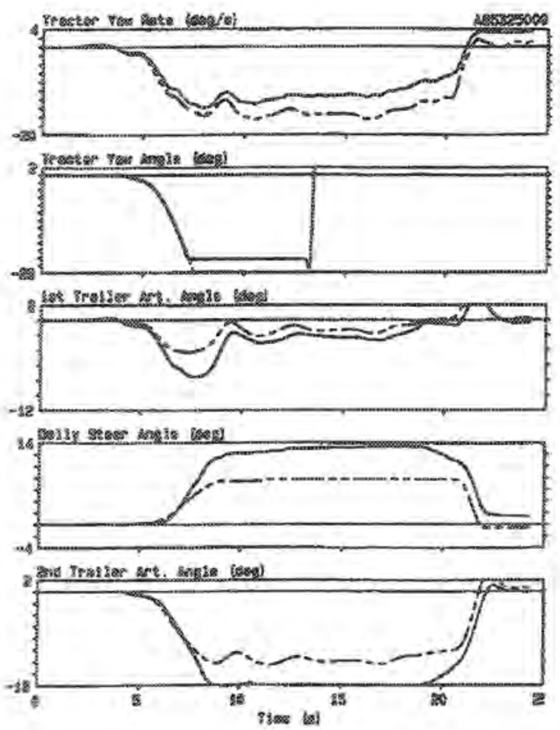
Computer simulation was conducted for the C-train triple in the steady circular turn manoeuvre at each test speed. Figure 13 compares the vehicle responses at a speed of 47 km/h. There is excellent agreement for lateral acceleration of all the vehicle units and good agreement for the roll angle, except for the third trailer roll, which was drifting. Excellent agreement can also be observed between test and simulation in the tractor yaw angle, trailer articulations, and the first dolly steer angle. While the simulation model predicted a similar steer response at the second dolly, the test result showed a different steer pattern, which is a little doubtful. Similar agreement between test and simulation was obtained at other vehicle speeds.

4.2.3 6-Axle 48 ft Semi

Computer simulations were conducted for the 6-axle 48 ft (14.63 m) semi undergoing a steady circular turn for a number of vehicle speeds, ranging from 35 to 63 km/h, during which the trailer experienced a heavy touchdown of the outrigger. With this vehicle configuration, tires squealed even at the lower speeds, indicating that there was significant tire skidding along the circular path. Figure 14 compares the responses at a speed of 55 km/h. There was excellent agreement in the directional and roll responses of both the tractor and semitrailer. Test observation indicated that, at this speed, the inner wheels of one semitrailer axle were airborne. Similar agreement between simulation and test responses was obtained up to the threshold of instability.

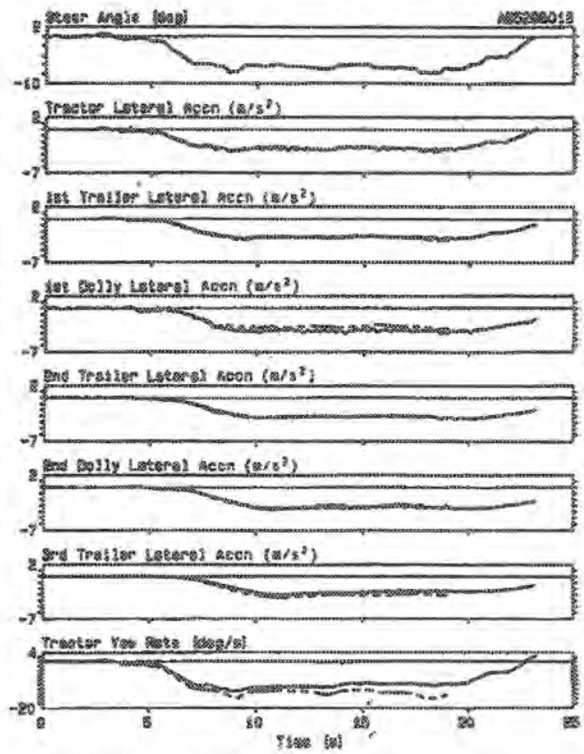
4.2.4 7-Axle 48 ft Semi

Computer simulation of the 7-axle 48 ft (14.63 m) semi was conducted at speeds of 35, 40, 47, and 55 km/h for the steady circular turn manoeuvre. Results of the simulation indicated that, with the existing tire characteristics, the simulation model failed to produce a close prediction of the lateral acceleration response of the vehicle even at a low speed of 35 km/h. Figure 15 compares the vehicle response between test and simulation at a speed of 35 km/h. Test observation revealed that some of the tires at the trailer rearmost axle had developed an irregular wear pattern resulting from



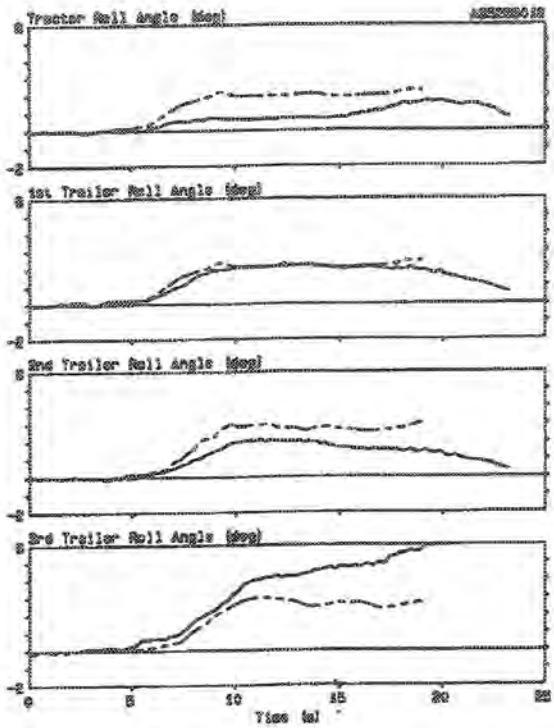
C-train double, steady circular turn responses at 55 km/h

FIGURE 12b



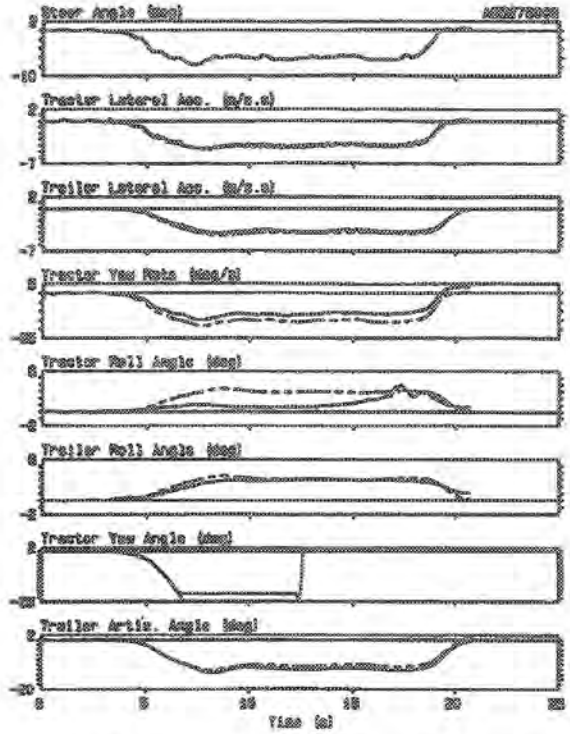
C-train triple, steady circular turn responses at 47 km/h

FIGURE 13a



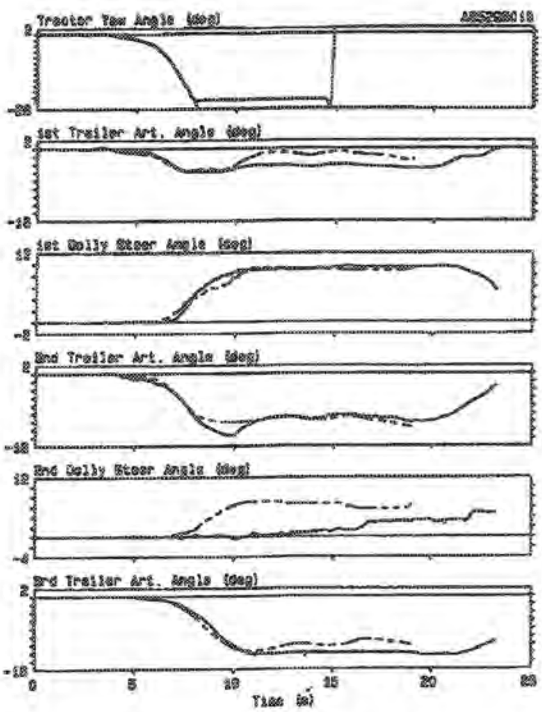
C-train triple, steady circular turn responses at 47 km/h

FIGURE 13b



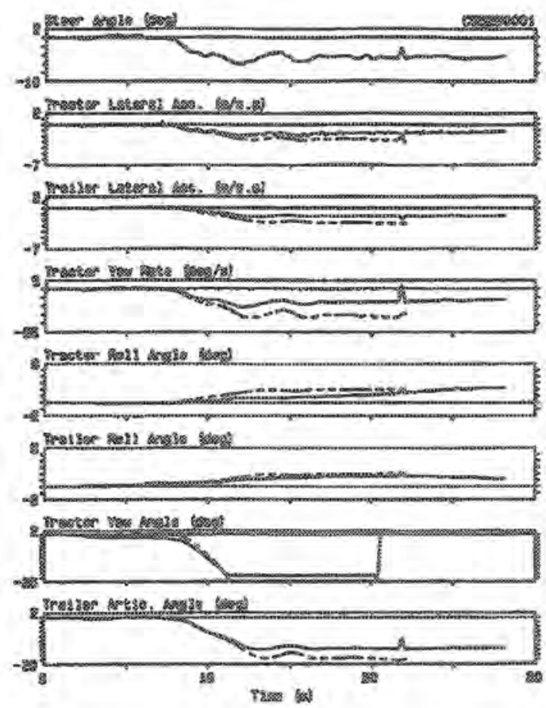
6-axle 48 ft semi steady circular turn responses at 35 km/h

FIGURE 14



C-train triple, steady circular turn responses at 47 km/h

FIGURE 13c



7-axle 48 ft semi circular turn responses at 35 km/h

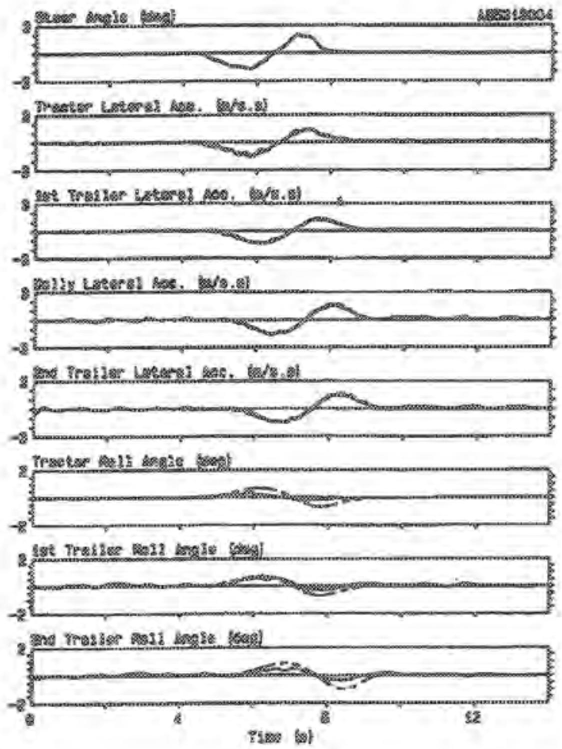
FIGURE 15

the earlier test of the 5- and 6-axle configurations of this combination. It is likely that these tires had a very different cornering characteristic than that used in the simulation, especially for this manoeuvre. Due to the scope of this work, no further attempt was made to refine the tire data for this vehicle. However, it is believed that better agreement between simulation and test response could be obtained by reducing the tire cornering capacity at the semi-trailer's rearmost axle.

4.3 SINUSOIDAL STEER

In this manoeuvre, the driver approached an open high-friction test area at constant speed with a loaded vehicle and executed a sinusoidal steer input at the steering wheel. This created a sinusoidal lateral acceleration input at the tractor, which resulted in a sidestep to the left dependent on the speed and steer amplitude, a vehicle trajectory similar to the single lane change. The sinusoidal steer was simply a standard input used to determine the vehicle's stability characteristics.

The test was run at speeds of 63, 84, and 94 km/h, which were the actual speeds in the gear that came closest to the target speeds of 60, 80, and 100 km/h. Steer periods within the range of 1 to 5 s were used.



A-train double, sinusoidal steer responses at 63 km/h, 3.8 s steer period

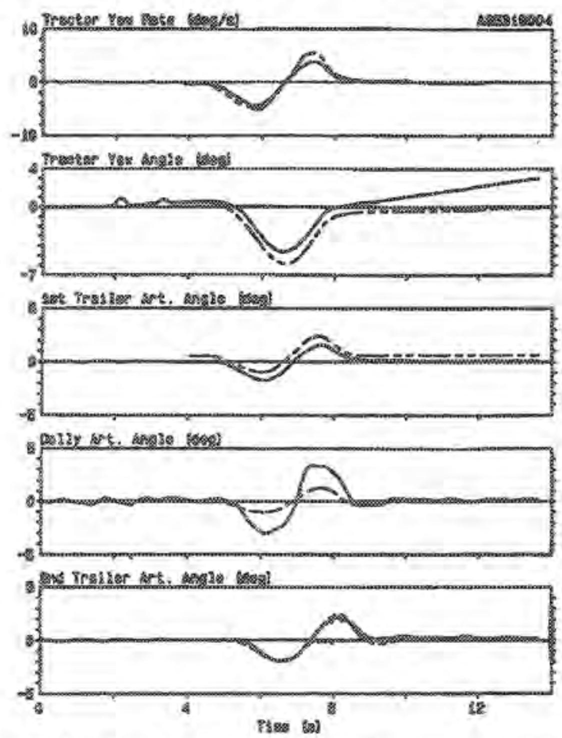
FIGURE 16a

4.3.1 A-Train Double

Simulation of the sinusoidal steer manoeuvre of the A-train double was conducted at 63 and 94 km/h.

Figure 16 shows excellent agreement between simulation and test results for the lateral acceleration and articulation responses of all the vehicle units at a speed of 63 km/h. The difference in the dolly articulation angle is due to malfunction of the articulation measuring device at the pintle hook. Similar agreement between test and simulation was obtained with different steer periods.

The stability of various configurations can be summarized in terms of rearward amplification, which is the ratio of the lateral acceleration of the rearmost unit to that of the tractor. Figure 17 compares the rearward amplification of the A-train double as a function of steer period at 63 and 94 km/h. In this and subsequent figures for the rearward amplification, the symbol plus represents test results and the square represents simulation results. Both the test and simulation results show a similar trend in the rearward amplification as a function of steer period for both vehicle speeds.



A-train double, sinusoidal steer responses at 63 km/h, 3.8 s steer period

FIGURE 16b

4.3.2 A-Train Triple

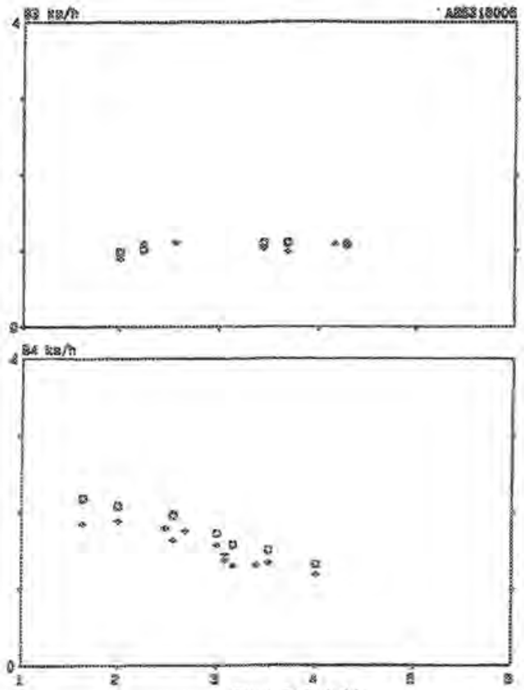
Simulations were performed at the vehicle speeds of 63, 84, and 94 km/h with the sinusoidal steer manoeuvre for the A-train triple at different steer periods. Figure 18 shows the comparison of the dynamic responses of the A-train triple between simulation and test results at 84 km/h, with a steer period of 2 s. Simulation results for the directional response of all the vehicle units agree well with the test responses, and there is good correlation for the roll responses at 84 km/h. The difference in first-dolly lateral acceleration was possibly due to the roll response of the A-dolly. Simulation results indicated that, at 94 km/h, the simulation model can still predict the dynamic responses of the test vehicle, except that the simulation predicted a higher damping at the end of the steering manoeuvre. Similar agreement was found at other operating conditions. Figure 19 shows the simulated rearward amplification superimposed on that of the test results as a function steer period at 63, 84, and 94 km/h. There is a definite agreement between test and simulation in the trend of rearward amplification as a function of steer period.

4.3.3 5-Axle 48 ft Semi

Both computer simulation and test were conducted for the 5-axle semi with the sinusoidal steer manoeuvre at 63, 84, and 94 km/h. Figures 20, 21, and 22 show the simulated response superimposed on the test results at 63, 84, and 94 km/h, respectively, with a steer period in the 2 to 3 s range. There is excellent agreement in the directional response of all the vehicle units below 84 km/h. Although simulation did not predict the measured peak roll angle of the tractor and trailer, there was a good correlation in the roll response. At 94 km/h, the model predicted a somewhat different response than the test responses. This is possibly due to the difference in the tire characteristics between test and simulation, which showed up when the vehicle was operating at higher speed. Similar agreement was obtained at the other steer periods. Figure 23 shows the comparison of the trailer rearward amplification as a function of steer period between simulation and test results at 63, 84, and 94 km/h. There is excellent agreement in the trend of the rearward amplification with respect to steer period between test and simulation for the three speeds examined.

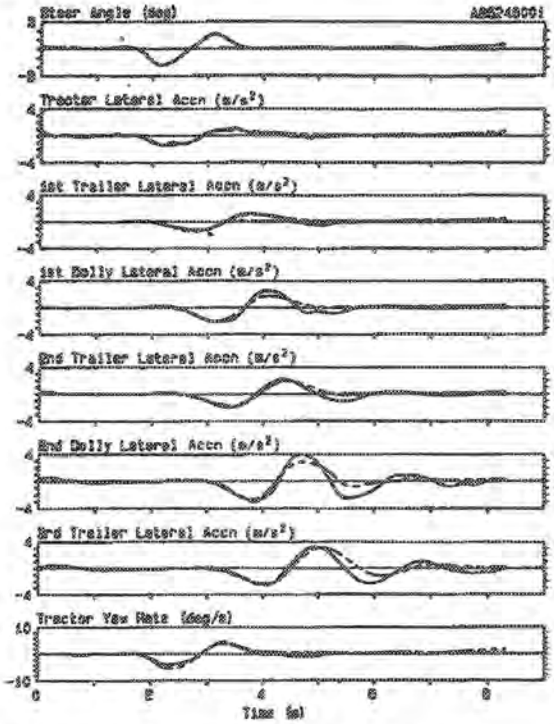
5. DISCUSSION

One of the major concerns facing the transfer of a relatively large computer program from a mainframe to a minicomputer is the execution



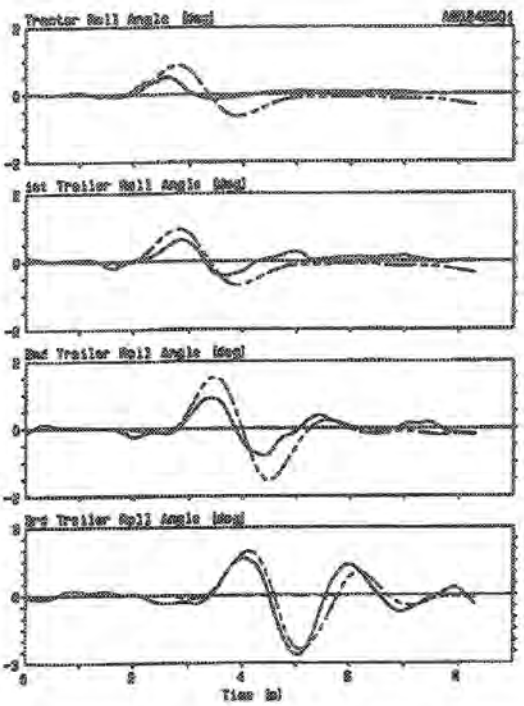
A- train double rearward amplification vs steer period

FIGURE 17



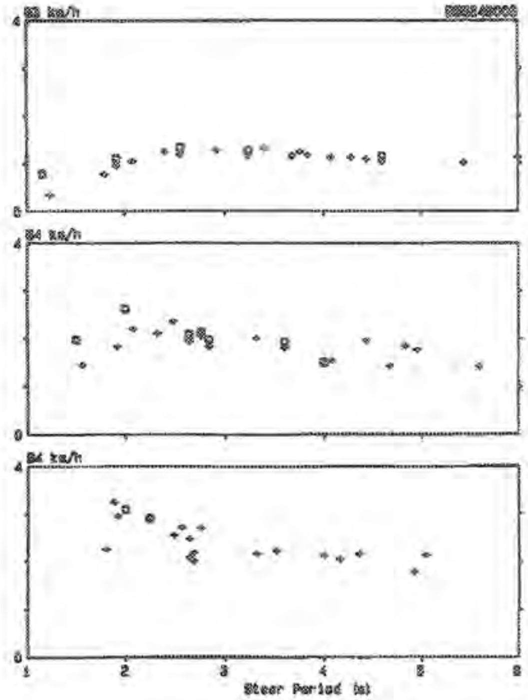
A-train triple, sinusoidal steer responses at 84 km/h, 2.0 s steer period

FIGURE 18a



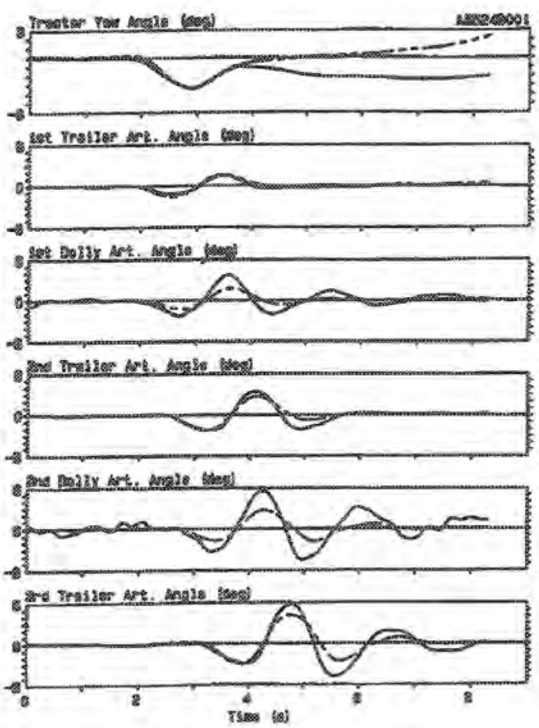
A-train triple, sinusoidal steer responses at 84 km/h, 2.0 s steer period

FIGURE 18b



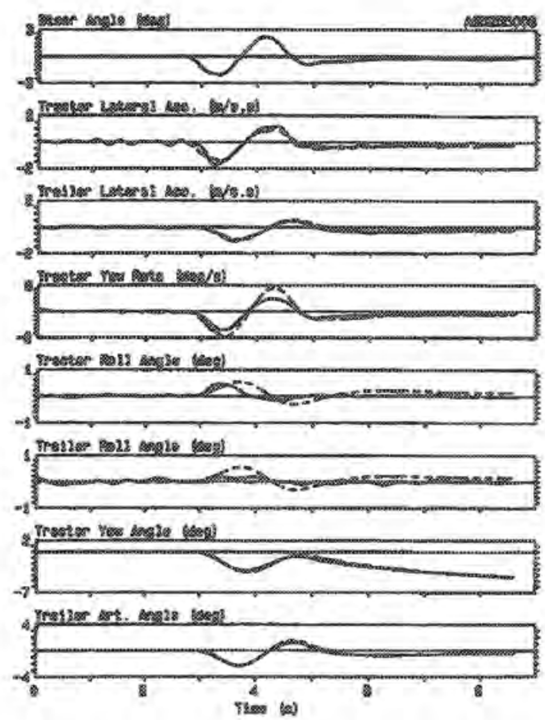
A-train triple rearward amplification vs steer period

FIGURE 19



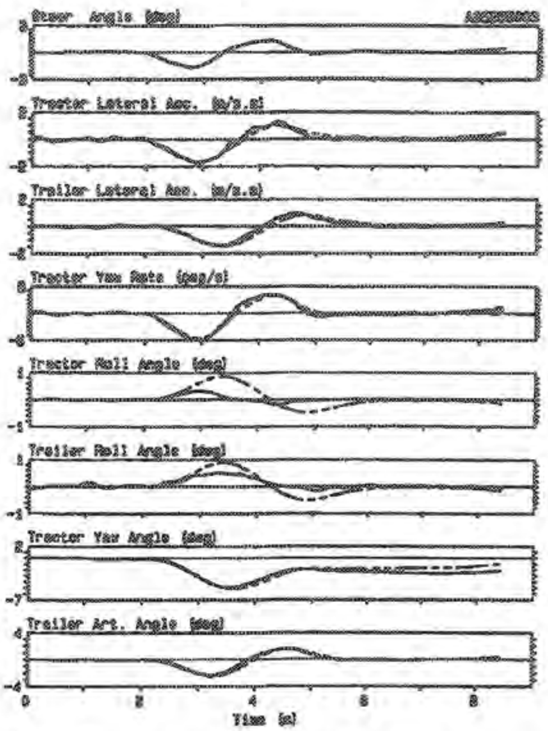
A-train triple, sinusoidal steer responses at 84 km/h, 2.0 s steer period

FIGURE 18c



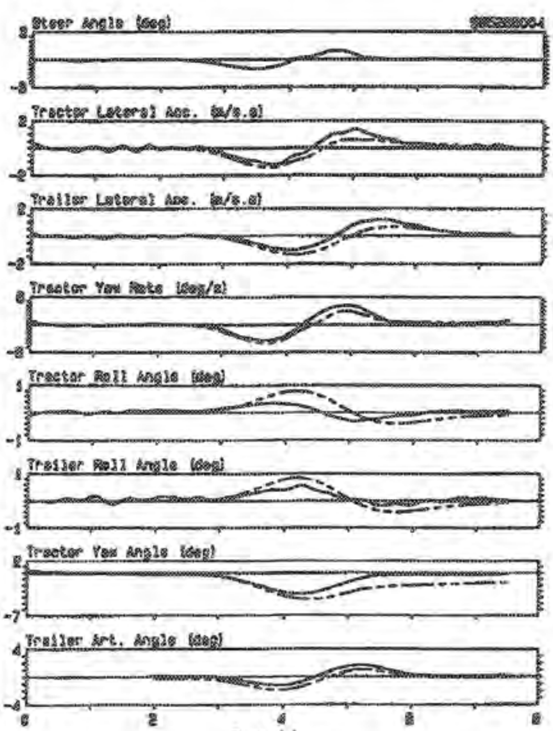
5-axle 48 ft semi, sinusoidal steer responses at 63 km/h, 2.0 s steer period

FIGURE 20



5-axle 48 ft semi, sinusoidal steer responses at 84 km/h, 2.7 s steer period

FIGURE 21

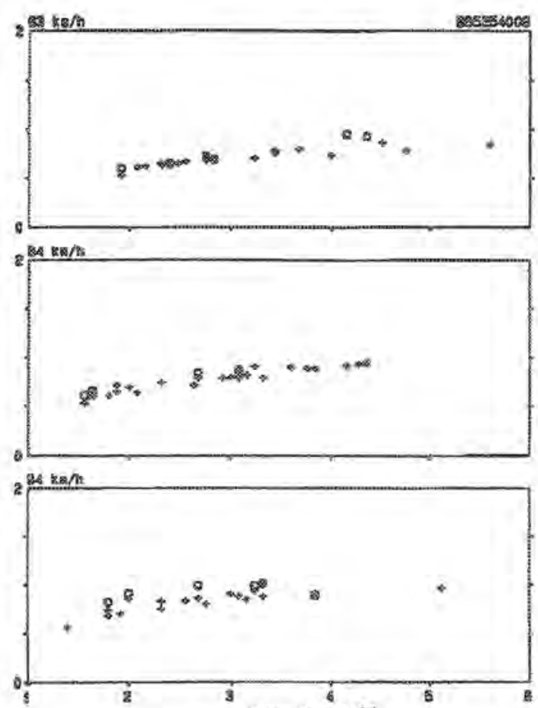


5-axle 48 ft semi, sinussoidal steer responses at 94 km/h, 3.0 s steer period

FIGURE 22

speed. With the original yaw/roll program, the execution speed was painfully slow. The speed ratio for an 8-axle tractor semitrailer was 400:1. In other words, the program required 400 s of computing time to generate 1 s of data. After all the code simplification, reduction in matrix algebra, and use of vector instructions, the execution speed ratio was improved to about 100:1. Thus, the new version was four times faster than the original yaw/roll program on the HP-1000 minicomputer. Table 3 shows the execution speed ratio for the nine vehicle configurations simulated in this program. It ranges from a low of 74:1 for the 5-axle semi to a high of 250:1 for the triples combinations.

It was found during the course of modifying the UMTRI yaw/roll program that there was a problem with the modelling of the pintle hook mechanism. The analysis assumed that with the pintle hook arrangement, the trailing unit is free to bounce, roll, yaw, and pitch with respect to the towing unit. Using this assumption, simulation of an A-train double terminated after a few steps because of numerical problems in the integration process. Examination of the vehicle response revealed that there was an unstable pitch motion of the dolly, a direct result of the lack of a pintle hook vertical



5-axle 48 ft semi rearward amplification vs steer period

FIGURE 22

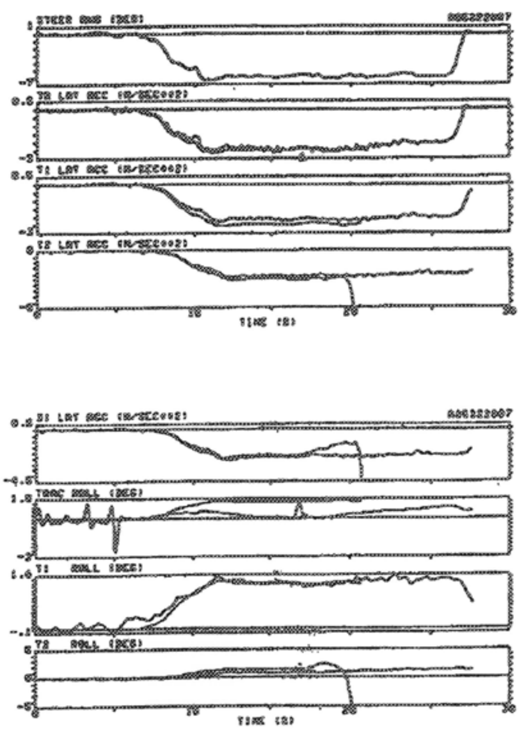
constraint. The problem could be avoided for the first 8 s if the dolly centre of mass, axle, and fifth wheel placement were all assumed at the same longitudinal position. However, if the simulation was extended further, an "unexpected" rollover of the trailing unit occurred due to the dolly pitch motion, as shown in Figure 24 for an A-train double undergoing a steady circular turn manoeuvre at a speed of 40 km/h. By imposing a vertical reaction at the pintle hook in the MTC program, the "unexpected" rollover was suppressed, as shown in Figure 25 for the same manoeuvre.

Table 3 – Simulation speed ratio of various configurations

Vehicle configuration	Simulation speed ratio
5-axle 45 ft semi	74
5-axle 48 ft semi	74
6-axle 48 ft semi	82
7-axle 48 ft semi	90
B-train double	120
A-train double	144
C-train double	144
A-train triple	250
C-train triple	250

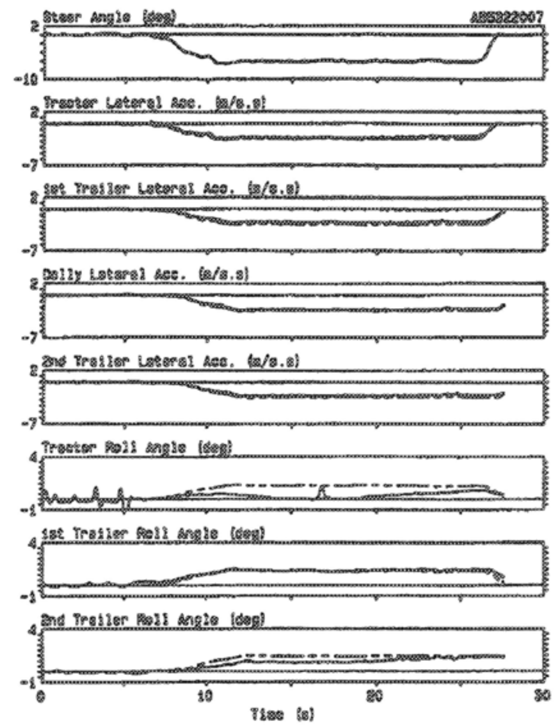
The result of this study has demonstrated the effect of tire wear on the directional response of the vehicle. It was observed that some of the tires at the rearmost axle of the 48 ft (14.63 m) semi developed an irregular wear pattern as a result of earlier tests in the 5- and 6-axle semi configurations. Thus, the tires of the 7-axle 48 ft (14.63 m) semi had a somewhat different characteristic than the original tire data. The effect of this was demonstrated in the steady circular turn manoeuvre, at which the simulated response was higher than the test responses. Furthermore, some vehicle configurations were found to be much more sensitive to the tire characteristics than others, such as the B-train double and the 7-axle 48 ft (14.63 m) semi. Proper data must be used to generate results that are representative of the actual vehicle responses.

Even though efforts were made to select input data that were representative of the physical component, it was not possible to get the precise characteristics of all components because of a lack of measured data. The tractor front suspension compliances and tractor drive axle tire characteristics are two examples where no data were available, and the input characteristics were selected from existing data that were considered



A-train double, steady circular turn responses at 40 km/h (no vertical restraint)

FIGURE 24



A-train double, steady circular turn responses at 40 km/h (with vertical restraint)

FIGURE 25

to come closest to the actual component. Data for the other suspension compliances and tire characteristics were selected from the generic product (16). All of these may affect, to a certain extent, the directional and roll responses of the vehicle.

Some vehicles experienced a significant drop in speed when they made the steady circular turn. Clearly, this affects the steer angle, lateral acceleration, yaw rate, and other responses. The simulations all assumed steady initial speed through the manoeuvre. It would have been possible to enter the forward speed as tabular input in the same way as the steer input. However, the Euler equations in the model assume a constant forward speed, and to permit longitudinal acceleration would have taken a great deal more effort than time permitted. Since longitudinal acceleration was low, it might have been a reasonable approximation to interpolate the "constant" speed in the same way as the steer input, but this was not tried. Because of these differences, the path followed by the vehicle in the simulation often diverged quite far from the actual path. There was also divergence of the path followed by the vehicle in the simulation from the actual path in the lane change manoeuvre. In this case, however, the divergence was due to small differences in initial yaw angle and yaw rate, as well as vehicle slide, integrated over a fairly long period. Both of these divergences are a consequence of using the measured steer input. When it is necessary to simulate a vehicle following a specific path, the yaw/roll program permits the path to be specified and requires the use of its driver model in a closed-loop mode of operation (14). This feature was not needed in this work, so was omitted to reduce memory requirements.

When simulation of a given test run was conducted using the measured steer input, certain responses were obtained which depended upon the model, its implementation as a computer program, and the input data which represent the subsystem and components. While the test responses may be different for the same operating condition because of small variations in steer input and random and non-random variables, such as wind effect, tire wear, road friction characteristics, etc., the computer program should give precisely the same results with the same input data. If the computer program is numerically stable, it is expected that a series of simulations, each using the steer input of a test run, would have similar variations to the variation between test responses if the model and data are reasonably representative of the actual vehicle. There remain, however, sample variations between tires and suspensions, for instance, and, possibly, assumptions regarding quantities such as hitch and frame stiffnesses. It is legitimate to suppose that variation in such data, over a range reasonable to represent the production and wear differences between these components, will result in differences in responses that are not large when compared to the gross response.

This type of comparison was not investigated in this work. Most test conditions were only run twice, with further repetitions only when earlier runs were obviously deficient. This was necessary to maintain schedule with a test program of this scope. There was, then, no clear need to conduct parametric variations in the simulation, except as appeared necessary where assumed values were adjusted to improve the match between test and simulation in an overall sense. This work has been concerned more with an overall impression resulting from nine vehicles in three manoeuvres and various test conditions than with a detailed and precise match for just a few conditions. It is evident that simulation results can be made to match test data from individual runs if the proper data are used, whether that data are obtained by direct measurement or deduced, as necessary, to achieve a match. However, if generic data result in a reasonable agreement for individual runs, say within the repeatability of individual test runs, and they also give the trend observed in test over a number of runs, then this work creates confidence that the simulation is broadly applicable.

6. CONCLUSIONS

The UMTRI yaw/roll program has been successfully installed on the HP-1000 microcomputer at MTC. Simplification of the program code and utilization of the computer system's vector instructions enabled the modified program to execute in a reasonable time.

The program was extended to allow simulation of triple trailer combinations up to a maximum of six vehicle units. By including the improved version of the B-dolly model developed at UMTRI, the MTC version is capable of simulating a C-triple train with steerable axles.

In spite of shortcomings in the input data, and other details that cannot be, or have not been, represented in the model, the yaw/roll program still provided a reasonable prediction of the dynamic responses for most of the vehicle configurations, namely, the 5-axle 45 ft (13.72 m) and 48 ft (14.63 m) semis, A- and C-train doubles, and A- and C-train triples, in the sinusoidal steer and lane change manoeuvres over a wide range of speeds and steer periods.

It was also demonstrated that if a better representation of the tire characteristics at the tractor drive axles was used, the yaw/roll program was capable of predicting a fairly accurate response of the B-train double and the 6- and 7-axle 48 ft (14.63 m) semitrailers in the sinusoidal steer and lane change manoeuvres and all vehicles except the 7-axle 48 ft (14.63 m) semi in the steady circular turn.

This study has shown that, with the proper input data, the yaw/roll program can provide fairly accurate prediction of the directional and roll responses of a wide range of vehicle configurations under various steering manoeuvres and operating conditions.

7. ACKNOWLEDGEMENTS

This work was conducted on behalf of the CCMTA/RTAC Vehicle Weights and Dimensions Study, managed by J.R. Pearson. The original yaw/roll program was provided by University of Michigan Transportation Research Institute (UMTRI). Tire characteristics and suspension properties and compliances were taken directly from UMTRI's laboratory measurements performed on behalf of the study.

Testing was conducted by the staff of the Automotive Technology and Systems Office: J.R. Billing; N.R. Carlton; G.B. Giles; W. Mercer, P.Eng.; W.R. Stephenson, P.Eng.; and M.E. Wolkowicz; and assigned students G. Goertzen, S. Jazic, and D.R. Sykes.

The assistance and support of all involved are hereby acknowledged with gratitude.

The author also thanks the Technical Steering Committee of the Weights and Dimensions Study for approval to present this paper.

8. REFERENCES

1. "Vehicle Weights and Dimensions -- Bridge Capacity Study," Roads and Transportation Association of Canada, 1980.

2. Ervin, R.D., "A Survey of the Characteristics of Equipment in the Canadian Trucking Fleet," Interim Technical Report No. 1, Vehicle Weights and Dimensions Study, Roads and Transportation Association of Canada, Ottawa, November 1984.

3. Billing, J.R., Mercer, W., and Stephenson, W.R., "Procedures for Test of Baseline and Additional Vehicles," Ontario Ministry of Transportation and Communications, Transportation Technology and Energy Branch, Report CV-86-01, June 1986.

4. Billing, J.R., and Mercer, W., "Demonstration of Baseline Vehicle Performance: 45 ft Semi," Ontario Ministry of Transportation and Communications, Transportation Technology and Energy Branch, Report CV-86-02, June 1986.

5. Billing, J.R., and Mercer, W., "Demonstration of Baseline Vehicle Performance: A-Train Double," Ontario Ministry of Transportation and Communications, Transportation Technology and Energy Branch, Report CV-86-03, June 1986.

6. Billing, J.R., and Mercer, W., "Demonstration of Baseline Vehicle Performance: B-Train Double," Ontario Ministry of Transportation and Communications, Transportation Technology and Energy Branch, Report CV-86-04, June 1986.

7. Billing, J.R., and Mercer, W., "Demonstration of Baseline Vehicle Performance: C-Train Double," Ontario Ministry of Transportation and Communications, Transportation Technology and Energy Branch, Report CV-86-05, June 1986.

8. Billing, J.R., and Mercer, W., "Demonstration of Baseline Vehicle Performance: A-Train Triple," Ontario Ministry of Transportation and Communications, Transportation Technology and Energy Branch, Report CV-86-06, June 1986.

9. Billing, J.R., and Mercer, W., "Demonstration of Baseline Vehicle Performance: C-Train Triple," Ontario Ministry of Transportation and Communications, Transportation Technology and Energy Branch, Report CV-86-07, June 1986.

10. Billing, J.R., and Mercer, W., "Demonstration of Tractor-Trailer Performance: 5-Axle 48 ft Semi," Ontario Ministry of Transportation and Communications, Transportation Technology and Energy Branch, Report CV-86-08, June 1986.

11. Billing, J.R., and Mercer, W., "Demonstration of Tractor-Trailer Performance: 6-Axle 48 ft Semi," Ontario Ministry of Transportation and Communications, Transportation Technology and Energy Branch, Report CV-86-09, June 1986.

12. Billing, J.R., and Mercer, W., "Demonstration of Tractor-Trailer Performance: 7-Axle 48 ft Semi," Ontario Ministry of Transportation and Communications, Transportation Technology and Energy Branch, Report CV-86-10, June 1986.

13. Billing, J.R., Mercer, W.R.J., Lam, C.P., Wolkowicz, M.E., and Stephenson, W.R., "Tests of a B-Train Converter Dolly," Ontario Ministry of Transportation and Communications, Transportation Technology and Energy Branch, Report TVS-CV-82-111, June 1983.

14. Lam, C.P. and Billing, J.R., "Comparison of Simulation and Test of Baseline and Tractor-Trailer Vehicle," Ontario Ministry of Transportation and Communications, Transportation Technology and Energy Branch, Report CV-86-11, June 1986.

15. Gillespie, T.D., and MacAdam, C.C., "Constant Velocity Yaw/Roll Program: Users Manual," University of Michigan Transportation Research Institute, Report UMTRI-82-39, October 1982.

16. Ervin, R.D., and Guy, Y., "The Influence of Weights and Dimensions on the Stability and Control of Heavy Duty Trucks in Canada," Vehicle Weights and Dimensions Study Final Technical Report, Volume 2, Roads and Transportation Association of Canada, Ottawa, July 1986.

SESSION 9
PAVEMENT RESPONSE TO HEAVY VEHICLES 3

Chairman:

G. Ring
Transportation Research Board
United States