archive
74517

UMTRI-86-3

HEAVY TRUCK STABILITY: SYNTHESIS/PROGRAM PLAN DEVELOPMENT

P. S. Fancher
R. D. Ervin
T. D. Gillespie
C. B. Winkler
L. Segel

University of Michigan
Transportation Research Institute

February, 1986

UMTRI The University of Michigan
Transportation Research Institute

UMTRI-86-3

HEAVY TRUCK STABILITY: SYNTHESIS/PROGRAM PLAN DEVELOPMENT

P. S. Fancher
R. D. Ervin
T. D. Gillespie
C. B. Winkler
L. Segel

University of Michigan
Transportation Research Institute

February, 1986

Technical Report Documentation Page

1. Report No.

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
Heavy Truck Stability: Synthesis/Program Plan Development

5. Report Date
February, 1986

6. Performing Organization Code

7. Author(s) P.S. Fancher, R.D. Ervin, T.D. Gillespie, C.B. Winkler, L. Segel

8. Performing Organization Report No.
UMTRI-86-3

9. Performing Organization Name and Address
The University of Michigan
Transportation Research Institute
2901 Baxter Rd., Ann Arbor, MI 48109

10. Work Unit No.

11. Contract or Grant No.
DTNH22-84-D-07080

12. Sponsoring Agency Name and Address
National Highway Traffic Safety Administration
U.S. Department of Transportation
400 Seventh Street, S.W.
Washington, D.C. 20590

13. Type of Report and Period Covered
Final Report
9/1/85 to 3/1/86

14. Sponsoring Agency Code

15. Supplementary Notes
Task Order #5
Contract Technical Manager: Mr. Robert M. Clarke

16. Abstract

This report begins with a synthesis of knowledge pertaining to the handling, tracking, directional stability, and rollover performance of heavy trucks. It ends with a research plan for acquiring an information base that is intended to be sufficient for developing a reasoned set of performance standards that would enhance the safety of heavy trucks during vehicle maneuvers requiring steering control. The research program addresses an information base consisting of the following elements: (a) definitions of response phenomena, (b) inventories of the truck fleet, (c) demonstrations of the links to safety, (d) determinations of practical countermeasures, (e) development of regulatory procedures, and (f) cost and benefit projections. Time-scaled activity schedules and estimated costs are presented to provide guidance for assessing the magnitude of the effort required to assemble the information base.

17. Key Words
heavy truck stability
rollover
rearward amplification
offtracking, yaw instabilities

18. Distribution Statement
UNLIMITED

19. Security Classif. (of this report)
NONE

20. Security Classif. (of this page)
NONE

21. No. of Pages
99

22. Price

PREFACE

This document was prepared by the University of Michigan Transportation Research Institute (UMTRI) at the request of the National Highway Traffic Safety Administration (NHTSA). The purpose of the work requested of UMTRI by NHTSA was to develop a stand-alone section of the Section 216 Report to Congress called for in the Motor Carrier Safety Act of 1984 (PL98-554). Specifically, UMTRI's assignment was to focus on the heavy truck handling/stability portion of the report. The following material is the "section" that UMTRI submitted to NHTSA.

TABLE OF CONTENTS

Appendix A

1.0 INTRODUCTION

This document presents a synthesis of the state of knowledge and a plan for acquiring an information base that is sufficient for developing a reasoned set of safety standards pertaining to the handling, tracking, directional stability, and rollover performance of heavy trucks. Herein, performance characteristics related to the stability and control of heavy trucks are of interest because these characteristics clearly influence all maneuvers including those involved in accidents and especially those required for accident avoidance.

Directional control and stability, including rollover, of heavy trucks have been studied extensively in research programs conducted since 1970. The Motor Vehicle Manufacturer's Association, the National Highway Traffic Safety Administration, and the Federal Highway Administration have each supported substantial research programs whose findings are reported in the public domain (for example, see the bibliography appended to this Introduction). As a result of these efforts, research investigators now have comprehensive simulations for use in studying the responses of heavy trucks to steering inputs. Researchers have constructed facilities for measuring the mechanical properties of heavy truck components including tires, suspensions, steering systems, and mass and inertial characteristics as needed for using simulation models to predict vehicle performance and to plan vehicle test programs. Methodologies have been developed for conducting vehicle tests. Test results have been obtained to verify the validity of the models (indicating that the model builder's understanding of the phenomena involved is correct) and to demonstrate the situations in which the directional performance capabilities of heavy trucks are very limited. The current state of knowledge indicates that some heavy trucks have safety-related response problems identified as "rollover," "rearward amplification," "offtracking," and tendencies towards "yaw instabilities."

Although safety-related problems have recently been identified by vehicle dynamicists, current accident data files do not contain explicit information on the performance characteristics of the vehicles involved in accidents. There are good reasons for this. Accident investigators have not known what specific performance qualities to assess for heavy trucks. Even if the investigators had known what to assess, they would have been hard pressed to make realistic estimates of the levels of vehicle performance capabilities existing at the time of an accident. Nevertheless, vehicle dynamicists have found sufficient information in the accident record to allow them to make first order estimates of the influences of the performance levels of heavy trucks on the likelihood of a rollover accident. Furthermore, by studying particular types of articulated vehicle accidents, dynamicists have learned that certain design properties contribute to exaggerated responses of the rear trailers of doubles, triples, and truck-fulltrailer combinations.

Even though some progress has been made through using the accident record, the safety performance of heavy trucks, as relates to stability and control properties, currently is judged largely on the basis of how well a vehicle performs basic tasks required of all highway motor vehicles. Specifically, with regard to directional performance, it is desirable that a heavy truck should (a) remain upright (i.e., not rollover), (b) follow a desired path in response to steering, (c) maintain a limited swept path, and (d) not oscillate from side to side in an uncontrollable manner. To the extent that some heavy trucks have limited capabilities with respect to these fundamental goals, they are judged to be less safe than other trucks.

The synthesis of knowledge, which follows in Section 2, treats rollover, trailing fidelity (including offtracking and rearward amplification), directional stability, and response to steering control in a non-technical manner. This synthesis is intended to provide an understanding of the mechanics, significance, and potential for improvement of the vehicle response phenomena that are addressed in the research plan. The research program, presented in Section 3, is structured to use the existing comprehension of heavy truck dynamics to guide accident studies, fleet inventories, evaluations of feasible countermeasures, and the development of procedures appropriate for use in performance standards.

In particular, the research program is aimed at developing an information base that can be used to weigh the following propositions:

1) There is a level of rollover immunity that can be justified as a reasonable goal with regard to reducing the incidence of accidents involving the rollover of heavy trucks.

2) The rear end of long, possibly articulated, vehicles should follow (i.e., track) the motion of the front end with adequate fidelity. Acceptable levels of trailing fidelity can be specified for low-speed turning maneuvers, high-speed cornering, and obstacle-evasion situations in which rearward amplification (cracking the whip) may be significant.

3) Heavy trucks should be capable of operating on slippery surfaces without undue propensities to spin, jackknife, or otherwise lose directional control. Acceptable levels of turning performance can be specified for operating on slippery surfaces.

4) The response to steering of heavy trucks should be predictable and the driver should be able to handle the vehicle easily. Reasonable levels of steering gain and response time can be selected to improve steering controllability in emergency situations.

5) Commercial vehicles should possess adequate margins of directional stability. Acceptable levels of motion damping can be selected to provide safety margins for all modes of vehicle motion.

In the sense of the scientific method, these propositions are like hypotheses that are to be tested and evidence is to be gathered to either support or refute them.

<u>Bibliography</u>

1. Dugoff, H. "On the Influence of Aerodynamic Forces and Moments on the Lateral Stability of Articulated Highway Vehicles." <u>Proceed. of 1st Interna. Conf. on Vehicle Mechanics</u>, Swets & Zeitlinger, 1969, pp. 215-245.

2. Leucht, P.M. "The Directional Dynamics of the Commercial Tractor-Semitrailer Vehicle During Braking." SAE Paper No. 700371, 1970.

3. Leucht, P.M. "Directional Dynamics of the Tractor-Semitrailer Vehicle." Ph.D Thesis, Univ. of Michigan, 1970.

4. Dugoff, H. and Murphy, R.W. "The Dynamic Performance of Articulated Highway Vehicles--A Review of the State-of-the-Art." SAE Paper No. 710223, January 1971.

5. Segel, L., et al. "Ride and Handling Analysis of the AM General Transbus." Highway Safety Res. Inst., Univ. of Michigan, September 1972.

6. Bernard, J.E. "Some Time-Saving Methods for the Digital Simulation of Highway Vehicles." <u>Simulation</u>, Vol. 21, No. 6, December 1973, pp. 161-165.

7. Bernard, J.E., Winkler, C.B., and Fancher, P.S. "A Computer-Based Mathematical Method for Predicting the Directional Response of Trucks and Tractor-Trailers."

Phase II Tech. Rept., Highway Safety Res. Inst., Univ. of Michigan, Rept. No. UM-HSRI-PF-73-1, June 1, 1973.

8. Fancher, P.S., Winkler, C.B., and Bernard, J.E. "Computer Simulation of the Braking and Handling Performance of Trucks and Tractor-Trailers." Hit Lab Reports, Vol. 3, No. 5, January 1973, pp. 1-7.

9. Fancher, P.S., Winkler, C.B., and Bernard, J.E. "Simulation of the Braking and Handling of Trucks and Tractor-Trailers. Summary Report." Highway Safety Res. Inst., Univ. of Michigan, Rept. No. UM-HSRI-PF-73-2, January 13, 1973.

10. Segel, L., Fancher, P.S., and Bernard, J.E. "Computer Prediction of the Braking and Steering Performance of the AM General Transbus, a Summary Report." Highway Safety Res. Inst., Univ. of Michigan, Rept. No. UM-HSRI-PF-73-6, November 2, 1973.

11. Tielking, J.T., Fancher, P.S., and Wild, R.E. "Mechanical Properties of Truck Tires." SAE Paper No. 730183, January 1973.

12. Winkler, C.B. "Measurement of Inertial Properties and Suspension Parameters of Heavy Highway Vehicles." SAE Paper No. 730182, January 1973.

13. Bernard, J.E. "Articulated Vehicle Simulation: A Fresh Approach to Some Recurring Problems." Assoc. for Computing Machinery , 1974, pp. 540-549.

14. Bernard, J.E. "A Digital Computer Method for the Prediction of the Directional Response of Trucks and Tractor-Trailers." SAE Paper No. 740138, February-March 1974.

15. Bernard, J.E., Fancher, P.S., and Segel, L. "An Analysis of the Braking and Steering Performance of the AM General Transbus, Final Report." Highway Safety Res. Inst., Univ. of Michigan, Rept. No. UM-HSRI-PF-74-7, May 10, 1974.

16. Ervin, R.D. and Fancher, P.S. "Preliminary Measurements of the Longitudinal Traction Properties of Truck Tires." SAE Paper No. 741139, November 1974.

17. Ervin, R.D. and MacAdam, C.C. "Baseline Tests of the Longitudinal Traction Properties of Truck Tires." Highway Safety Res. Inst., Univ. of Michigan, Rept. No. UM-HSRI-PF-74-6, April 1974.

18. Winkler, C.B. "Analysis and Computer Simulation of the Four Elliptical Leaf Spring Tandem Suspension." SAE Paper No. 740136, February-March 1974.

19. "Commercial Vehicle Braking and Handling. Proceedings of a Symposium." Highway Safety Res. Inst., Univ. of Michigan, Rept. No. UM-HSRI-PF-75-6, 1975.

20. Bernard, J.E. "An Alternative to the Roll Axis for Use in Commercial Vehicle Simulation." Vehicle System Dynamics , Vol. 4, No. 4, December 1975, pp. 211-222.

21. Ervin, R.D., MacAdam, C.C., and Fancher, P.S. "The Longitudinal Traction Characteristics of Truck Tires as Measured on Dry Pavements." Highway Safety Res. Inst., Univ. of Michigan, Rept. No. UM-HSRI-PF-75-3, February 1975.

22. Moncarz, H.T., Bernard, J.E., and Fancher, P.S. "A Simplified, Interactive Simulation for Predicting the Braking and Steering Response of Commercial Vehicles." Highway Safety Res. Inst., Univ. of Michigan, Rept. No. UM-HSRI-PF-75-8, August 1975.

23. Ervin, R.D. "Lug-Tread Truck Tires: More Noise, Less Traction." HSRI Research , Vol. 7, No. 2, September-October 1976, pp. 1-6.

24. Ervin, R.D. "Tire Properties and Truck Handling: Some Surprising New Findings." HSRI Research , Vol. 7, No 1., July-August 1976, pp. 3-12.

25. Ervin, R.D. and MacAdam, C.C. " Noise and Traction Characteristics of Bias-Ply Truck Tires. Vol. 2: Wet Traction Findings." Final Rept., Highway Safety Res. Inst., Univ. of Michigan, Rept. No. UM-HSRI-76-2-2, October 1976.

26. Ervin, R.D. and Wild, R.E. "Noise and Traction Characteristics of Bias-Ply Truck Tires. Vol. 1: Noise and Dry Traction Findings." Highway Safety Res. Inst., Univ. of Michigan, Rept. No. UM-HSRI-76-2-1, January 1976.

27. Ervin, R.D., et al. "Effects of Tire Properties on Truck and Bus Handling." Final Rept., Contract No. DOT-HS-4-00943, Highway Safety Res. Inst., Univ. of Michigan, Rept. No. UM-HSRI-76-11, December 1976.

28. Segel, L. "The Impact of Truck Regulations from a Researcher's Point of View." Presented at West Coast Meeting, Society of Automotive Engineers, August 9-12, 1976.

29. Bernard, J.E. and Kim, T.M. "Modified Articulated Vehicle Simulation." Final Rept., Contract No. DOT-HS-6-5547, Highway Safety Res. Inst., Univ. of Michigan, Rept. No. UM-HSRI-76-23, April 1977.

30. Ervin, R.D. "Measurements of the Longitudinal and Lateral Traction Properties of Truck Tires." Braking of Road Vehicles Conference, Loughborough, England, 23-25 March 1976. Mechanical Engineering Publications, 1977, pp. 93-100.

31. Ervin, R.D. "Noise and Traction Characteristics of Radial-Ply Truck Tires." Final Rept., Contract No. DOT-OST-60157, Highway Safety Res. Inst., Univ. of Michigan, Rept. No. UM-HSRI-77-5, January 1977.

32. Segel, L. and Ervin, R.D. "The Influence of Tire Factors on the Stability of Trucks and Tractor-Trailers." Proceedings, HOPE Interna. Symposium, Tokyo, Japan, 1977, pp. 281-292.

33. Winkler, C.B. and Gillespie, T.D. "On the Directional Response Characteristics of Heavy Trucks." Vehicle System Dynamics, Vol. 6, No. 2-3, September 1977, pp. 120-123.

34. Ervin, R.D. "The Dynamic Stability of Fuel-Carrying Double-Tanker Trucks in Michigan." HSRI Research Review, Vol. 8, No. 6, May-June 1978, pp. 1-19.

35. Ervin, R.D., et al. "Ad Hoc Study of Certain Safety-Related Aspects of Double-Bottom Tankers." Final Rept., Highway Safety Res. Inst., Univ. of Michigan, Rept. No. UM-HSRI-78-18, Sponsored by Mich. State Office of Highway Safety Planning, Contract No. MPA-78-002A, May 7, 1978.

36. Gillespie, T.D. "Validation of the MVMA/HSRI Phase II Straight Truck Directional Response Simulation." Highway Safety Res. Inst., Univ. of Michigan, Rept. No. UM-HSRI-78-46, October 1978.

37. Gillespie, T.D. and Verma, M.K. "Analysis of the Rollover Dynamics of Double-Bottom Tankers." SAE Paper No. 781065, December 1978.

38. Mallikarjunarao, C. and Fancher, P.S. "Analysis of the Directional Response Characteristics of Double Tankers." SAE Paper No. 781064, December 1978.

39. Winkler, C.B., Nisonger, R.L., and Ervin, R.D. "Testing the Michigan Double-Bottom Tanker." SAE Paper No. 781066, December 1978.

40. Ervin, R.D. "Improving Anti-Roll Properties of Semitrailers, Road Tractors, and Heavy Trucks." HSRI Research Review , Vol. 9, No. 5, March-April 1979, pp. 7-8.

41. Ervin, R.D., Nisonger, R.L., and Mallikarjunarao, C. "Eliminating Yaw Instability in Tractor-Semitrailers During Cornering." HSRI Research Review , Vol. 10, No. 1, July-August 1979, pp. 1-17.

42. Ervin, R.D., et al. "The Yaw Stability of Tractor-Semitrailers During Cornering." Final Report, Contract No. DOT-HS-7-01602, Highway Safety Res. Inst., Univ. of Michigan, Rept. No. UM-HSRI-79-21, June 1979.

43. Fancher, P.S., Mallikarjunarao, C., and Nisonger, R.L. "Simulation of the Directional Response Characteristics of Tractor-Semitrailer Vehicles." Highway Safety Res. Inst., Univ. of Michigan, Rept. No. UM-HSRI-79-9, March 1979.

44. Gillespie, T.D., et al. "Truck and Tractor-Trailer Dynamic Response Simulation--T3DRS." Final Rept., Contract No. FH-11-9330, Highway Safety Res. Inst., Univ. of Michigan, Rept. No. UM-HSRI-79-38, 1979.

45. Nisonger, R.L. and Ervin, R.D. "Measurement of Ride Vibrations on Semitrailers Incorporating Different Suspensions." Highway Safety Res. Inst., Univ. of Michigan, Rept. No. UM-HSRI-79-57, September 5, 1979.

46. Segel, L., et al. "Government Efforts to Regulate Heavy Truck Braking. Response to Advance Notice of Proposed Rulemaking: Air Brake Systems." HSRI Research Review , Vol. 9, No. 6, May-June 1979, pp. 1-16.

47. Winkler, C.B. and Hagan, M. "A Test Facility for the Measurement of Heavy Vehicle Suspension Parameters." SAE Paper No. 800906, August 1980.

48. Fancher, P.S., et al. "Measurement and Representation of the Mechanical Properties of Truck Leaf Springs." SAE Paper No. 800905, November 1980.

49. Verma, M.K. and Gillespie, T.D. "Roll Dynamics of Commercial Vehicles." Vehicle System Dynamics , Vol. 9, No. 1, January 1980, pp. 1-17.

50. MacAdam, C.C., et al. "A Computerized Model for Simulating the Braking and Steering Dynamics of Trucks, Tractor-Semitrailers, Doubles, and Triples Combinations--Users' Manual, Phase 4." Highway Safety Res. Inst., Univ. of Michigan, Rept. No. UM-HSRI-80-58, September 1, 1980.

51. Ervin, R.D. and Segel, L. "Contrasts in the Dynamic Properties Influencing the Pre-Crash Safety of Cars and Heavy Trucks." Proceedings , 24th Conf. of the Amer. Assoc. for Auto. Med., October 1980, pp. 273-286.

52. Fancher, P.S., MacAdam, C.C., and Mallikarjunarao, C. "Articulated Bus Dynamic Analysis." Highway Safety Res. Inst., Univ. of Michigan, Rept. No. UM-HSRI-81-33, January 30, 1981.

53. Segel, L. and Ervin, R.D. "The Influence of Tire Factors on the Stability of Trucks and Tractor-Trailers." Vehicle System Dynamics , Vol. 10, No. 1, February 1981, pp. 39-59.

54. Ervin, R.D., Nisonger, R.L., and MacAdam, C.C. "Measurement of Pavement/Truck Interaction Under Experimental Conditions." Interim Rept., Contract No. FH-11-9577, Highway Safety Res. Inst., Univ. of Michigan, Rept. No. UM-HSRI-81-15, March 1981.

55. Ervin, R.D. "Safer Gasoline Tankers for Michigan--An Interview with Robert D. Ervin." HSRI Research Review , Vol. 11, No. 5, March-April 1981, pp.

56. Winkler, C.B. "Descriptive Parameters Used in Analyzing the Braking and Handling of Heavy Trucks: Inertial Properties of Commercial Vehicles." Final Report, Highway Safety Res. Inst., Univ. of Michigan, Rept. No. UM-HSRI-81-19-2, April 1981.

57. MacAdam, C.C. and Fancher, P.S. "Descriptive Parameters Used in Analyzing the Braking and Handling of Heavy Trucks: Properties of Antilock Systems." Final Report, Highway Safety Res. Inst., Univ. of Michigan, Rept. No. UM-HSRI-81-19-5, May 1981.

58. Ervin, R.D. and Mallikarjunarao, C. "A Study of the Yaw Stability of Tractor-Semitrailer Combinations." Proceedings , 7th IAVSD-IUTAM Symposium on Dynamics of Vehicles on Roads and Tracks, Cambridge, England, September 1981.

59. Mallikarjunarao, C. and Segel, L. "A Study of the Directional and Roll Dynamics of Multiple-Articulated Vehicles." Proceedings , 7th IAVSD-IUTAM Symposium on Dynamics of Vehicles on Roads and Tracks, Cambridge, England, September 1981.

60. Sayers, M. and Gillespie, T.D. "The Effect of Suspension System Nonlinearities on Heavy Truck Vibration." Proceedings , 7th IAVSD-IUTAM Symposium on Dynamics of Vehicles on Roads and Tracks, Cambridge, England, September 1981.

61. Fancher, P.S. "Computer Simulation of Heavy-Truck Dynamics." HSRI Research Review , Vol. 12, No. 2, September-October 1981, pp. 1-16.

62. Fancher, P.S. (ed.). "Descriptive Parameters Used in Analyzing the Braking and Handling of Heavy Trucks - Measurements of the Longitudinal and Lateral Traction Properties of Truck Tires." Final Report, Highway Safety Res. Inst., Univ. of Michigan, Rept. No. UM-HSRI-81-19-3, October 1981.

63. Winkler, C.B. and Fancher, P.S. "Descriptive Parameters Used in Analyzing the Braking and Handling of Heavy Trucks: Steering and Suspension Systems." Final Report, Highway Safety Res. Inst., Univ. of Michigan, Rept. No. UM-HSRI-81-19-4, October 1981.

64. Ervin, R.D. "The Failure of Manhole Covers on Tank Trailers During Rollover." Proceedings , Symposium on Designing for Damage Prevention in the Transportation Environment, Gaithersburg, Md., October 1981.

65. Bernard, J.E., Ervin, R.D., and Segel, L. "Traction Modifications Resulting from Test-Induced Treadwear." Proceedings , Symposium on Frictional Interaction of Tires and Pavements, Akron, November 1981.

66. Ervin, R.D. and MacAdam, C.C. "Truck Tire Traction." Final Report, Contract No. DTNH-22-80-C-07093, Highway Safety Res. Inst., Univ. of Michigan, Rept. No. UM-HSRI-81-56, December 1981.

67. Gillespie, T.D., et al. "Truck Cab Vibrations and Highway Safety." Final Report, Contract No. DTFH-61-81-C-00083, Highway Safety Res. Inst., Univ. of Michigan, Rept. No. UM-HSRI-81-9, March 1982.

68. Mallikarjunarao, C. "Road Tank Design: Its Influence on the Risk and Economic Aspects of Transporting Gasoline in Michigan." Ph.D. Dissertation, Univ. of Michigan, 1982.

69. Segel, L. "Mechanics of Heavy-Duty Trucks and Truck Combinations Conference." Univ. of Michigan Summer Conferences, June 21-25, 1982.

70. Ervin, R.D. and MacAdam, C.C. "The Dynamic Response of Multiply-Articulated Truck Combinations to Steering Input." SAE Paper No. 820973, August 1982.

71. Gillespie, T.D. "Influence of Tire/Wheel Nonuniformities on Heavy Truck Ride Quality." Final Report, Highway Safety Res. Inst., Univ. of Michigan, Rept. No. UM-HSRI-82-30, September 1982.

72. Ervin, R.D. and Nisonger, R.L. "Analysis of the Roll Stability of Cryogenic Tankers." Final Report, Highway Safety Res. Inst., Univ. of Michigan, Rept. No. UM-HSRI-82-32, September 1982.

73. Gillespie, T.D. and MacAdam, C.C. "Constant Velocity Yaw/Roll Program: Users' Manual." Final Report, Transportation Res. Inst., Univ. of Michigan, Rept. No. UMTRI-82-39, October 1982.

74. Fancher, P.S. "The Transient Directional Response of Full Trailers." SAE Paper No. 821259, November 1982.

75. MacAdam, C.C. "A Computer-Based Study of the Yaw/Roll Stability of Heavy Trucks Characterized by High Centers of Gravity." SAE Paper No. 821260, November 1982.

76. Mallikarjunarao, C., Ervin, R.D., and Segel, L. "Roll Response of Articulated Motor Trucks During Steady-Turning Maneuvers." Proceedings, 103rd Winter Annual Meeting of Amer. Society of Mech. Engrs., Phoenix, November 1982.

77. Winkler, C.B., Fancher, P.S., and MacAdam, C.C. "Parametric Analysis of Heavy-Duty Truck Dynamic Stability." Final Report, Contract No. DTNH22-80-C-07344, Transportation Res. Inst., Univ. of Michigan, Rept. No. UMTRI-83-13, March 1983.

78. Ervin, R.D. et al. "Influence of Size and Weight Variables on the Stability and Control Properties of Heavy Trucks." Final Report, Contract No. FH-11-9577, Transportation Res. Inst., Univ. of Michigan, Rept. No. UMTRI-83-10, March 1983.

79. Nisonger, R.L. and Ervin, R.D. "Dynamic Behavior of the B-Type Converter Dolly." Final Report, Contract No. OSX82-00094, Transportation Res. Inst., Univ. of Michigan, Rept. No. UMTRI-83-44, September 1983.

80. Fancher, P.S. and Segel, L. "Offtracking Versus Stability and Dynamic Response of the Trackless Train." 8th IAVSD Symposium, Cambridge, Mass., August 15-19, 1983.

2.0 SYNTHESIS OF KNOWLEDGE ON TRUCK PERFORMANCE PHENOMENA

From an overall view, one might assert that all of the design and condition variables, plus the initial speed and turning conditions, are collectively "responsible" for yielding any undesired outcomes in response to control inputs. To some extent, this view is correct and all of us should be endeavoring to improve upon all the elements of the highway-driver-vehicle system which may be serving to degrade performance. Since we are concerned here with the vehicle, however, it seems appropriate to establish that the vehicle condition variables (such as loading, tire wear, etc.) and the environmental condition variables (such as pavement "friction", downgrade, etc.) are given and that every truck should be designed to cope effectively with the likely ranges of those variables. Further, if vehicles are to operate on public highways, the ability to perform well over the required range of speeds and path radii seems axiomatic. Finally, if the traffic environment is known to impose a variety of conflicts which will stimulate drivers to apply certain ranges of control inputs (as described by magnitudes, phases, and frequency content of steer, brake, and throttle actuation) then we should strive to see that vehicles be capable of responding to these inputs in ways that yield suitable performance.

As was mentioned in Section 1.0, some heavy vehicles have "problems" that may prevent them from achieving acceptable performance. Within the current state of knowledge, considerable progress has been made in identifying these problems and in relating many of them to the various categories of design, condition, and control input excitation which appear rather commonly. Below, we will describe a number of the more frequently-identified problems and indicate related characteristics which contribute to these problems. (The reader should note that the discussions of "problems", herein , are not intended as a condemnation of trucks but rather as a synopsis of the items which are known to have importance to the stability and control behavior of trucks.)

2.1 Rollover

Rollover is an easily distinguishable accident mode common to heavy trucks. It presents risks to both the truck driver and the general public. Rollover occurs when the lateral acceleration imposed on a truck exceeds the "threshold" that it can sustain. The lateral acceleration arises most commonly from cornering and/or cross-slope on the road, although other factors may contribute, such as lateral impacts on low barriers or curbs, tires digging into soft earth, etc. In trucking operations, rollovers happen when the level and duration of the imposed lateral acceleration is sufficient to roll the vehicle to an angle such that the driver cannot correct for the condition.

2.1.1 Mechanics of Rollover. The mechanisms that influence commercial vehicle roll stability in a steady turn are well understood [1]. Figure 2.1.1 illustrates that as a vehicle undergoes a turn, it experiences a centrifugal force pulling outward from the center of the turn through the vehicle's center of gravity (c.g.). This force tends to roll the vehicle outward from the turn, and if large enough, will cause the vehicle's inside tires to lift from the ground and roll the vehicle over.

The magnitude of this force is equal to the weight of the vehicle (W) times the lateral acceleration (a_y) generated by the turn. As the turn becomes more severe, lateral acceleration increases, causing an increase in the centrifugal force. Thus, the roll stability limit of the vehicle is generally identified by the maximum level of lateral acceleration which a vehicle can sustain without rolling over.

In addition to the centrifugal force, Figure 2.1.1 also shows that, as the vehicle rolls outwardly in a turn, its c.g. tends to shift outwardly relative to the vehicle's track. This outward shift of the c.g. also tends to promote rollover, serving to lower the roll stability level.

In steady turning situations where the driver must follow a constant radius (e.g., exit ramps), a static, or quasi-static, rollover threshold can be defined from an analysis of the moments acting on the vehicle [2]. The rollover threshold is described by the lateral acceleration level at which the net roll-resisting moment reaches its maximum. Figure 2.1.2 illustrates this threshold on a plot of roll moment versus roll angle for a typical vehicle. In a turn, the lateral acceleration produces a roll moment and an associated roll angle on the vehicle. The vehicle is stable so long as the lateral acceleration does not exceed the peak level of the curve. When it does exceed the peak, it is exceeding the vehicle's ability to resist rollover. At this point irrecoverable rollover begins.

A number of vehicle parameters can be identified which affect the roll stability limit of a vehicle. Generally, these parameters either (1) determine the direct effectiveness of the centrifugal force in generating rollover, or (2) contribute to determining the amount of outward shift of the center of gravity in a given turn.

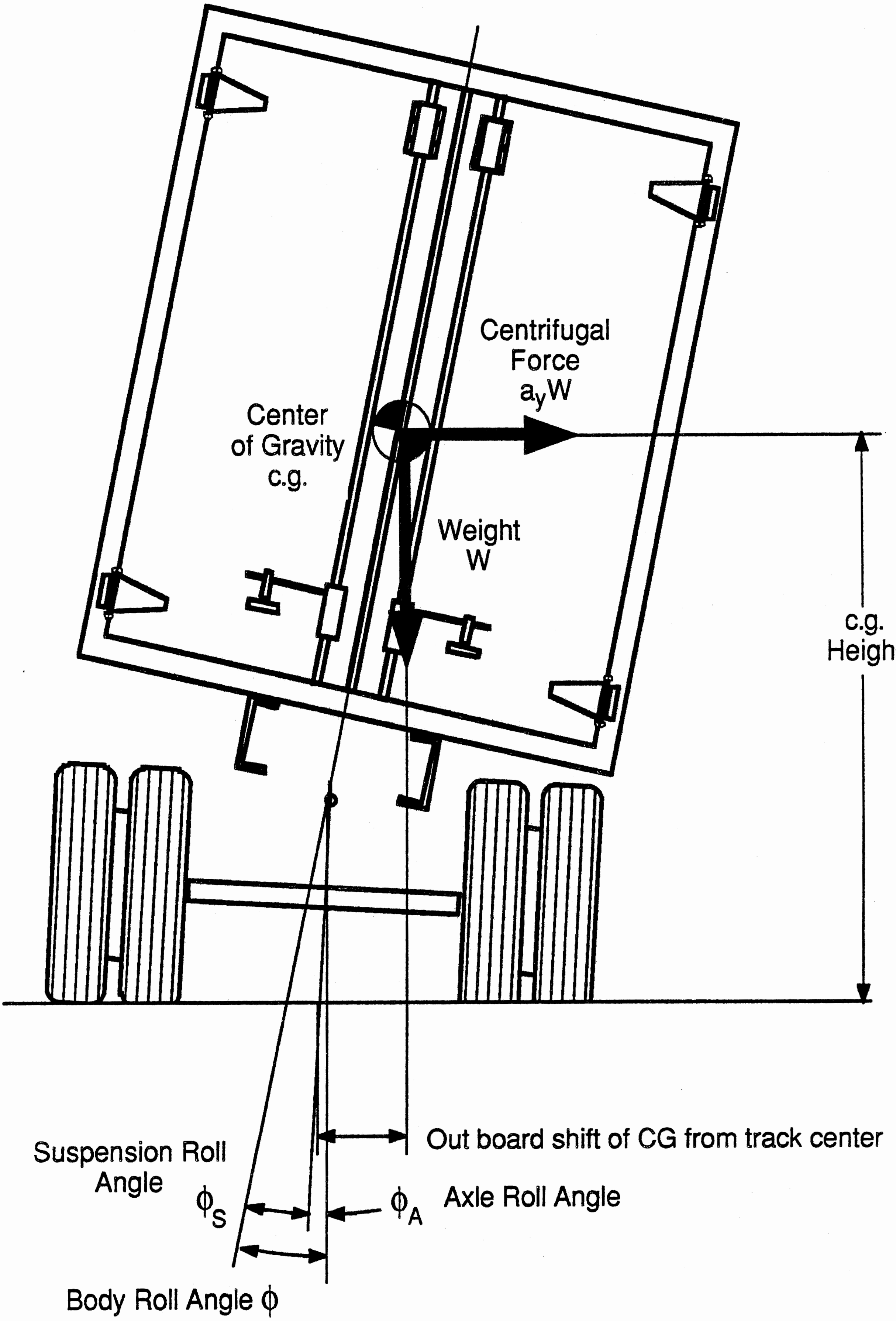


Figure 2.1.1 A heavy truck in a left turn

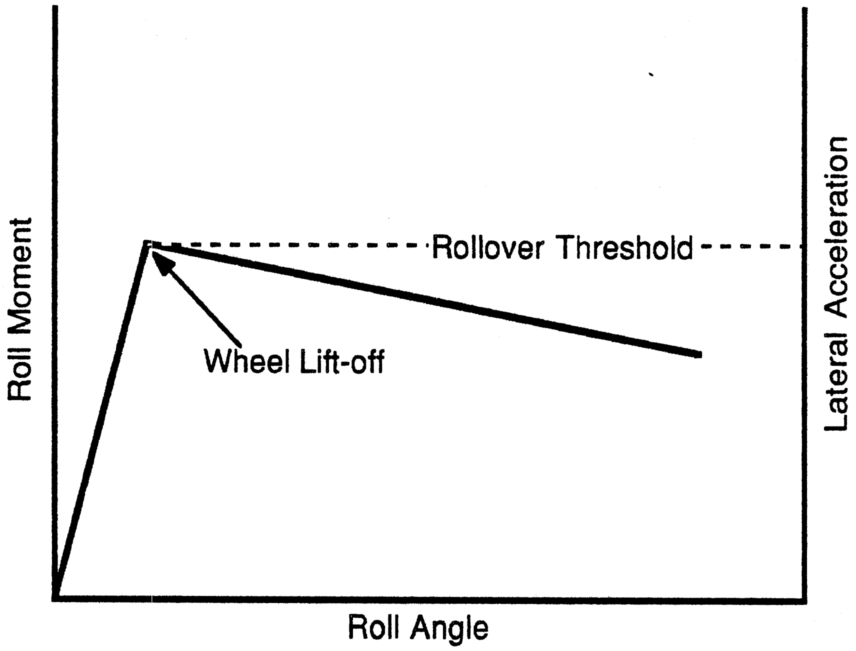


Fig. 2.1.2 Roll response of a truck

The ratio of half of the track width to c.g. height is the most basic vehicle parameter determining vehicle roll stability. It is the one parameter which establishes "the direct effectiveness of the centrifugal force in generating rollover." As the ratio is increased, either by increasing track width or decreasing c.g. height, the roll stability of the vehicle is improved.

Other vehicle parameters have a significant effect on roll stability, but they do so through influencing the secondary mechanism of the outboard shift of the c.g. due to roll. Recognizing, however, that this "secondary" effect can reduce roll stability on the order of 50 percent relative to the "rigid" vehicle, these parameters can definitely have a significant influence. The more important of these vehicle properties include (1) the general level of roll stiffness of the vehicle suspensions and tires, including the influence of suspension lash, (2) suspension geometry; in particular, the heights of the suspension roll centers, and (3) the distribution of stiffnesses among the various suspensions of the vehicle.

Vehicle properties that are important to rollover can be related to current practices in assembling and loading commercial vehicles, namely,

1) Trailers built in van and platform configurations establish a loading floor at a height which is approximately 25 percent greater than the effective "half-track" dimension. Thus any payload placed on that floor is strongly capable of destabilizing the vehicle in roll.

2) Much of American truck transportation involves the cartage of relatively low-density freight such that the cargo is commonly stacked to nearly the maximum height dimension (which is constrained only by bridge clearance considerations).

3) Even bulk-commodity tank trailers are commonly constructed as either circular or elliptical cylinders, without drop bottoms, such that the height of their centers of gravity are also typically far above the level of the half-track value.

4) Tractor and trailer suspensions do not employ roll stiffness levels which are uniformly proportioned to the loads carried on the respective axles.

5) Tractor steering axles are conspicuously deficient in roll stiffness level, given the value of front axle load which is carried.

6) Leaf-spring suspensions employed on tractor drive axles and trailer axles commonly incorporate substantial levels of spring lash which serves to reduce the effective roll stiffness.

7) Certain truck suspensions have conspicuously low roll-centers, causing a greater portion of the imposed roll moment to be borne by the suspension springs.

8) Truck and tractor frames have low levels of torsional stiffness rendering the "roll-assistance" of the front axle suspension less effective.

9) The lash present in fifth wheel assemblies can degrade the roll stability of tractor semitrailers having very high centers of gravity.

10) Certain types of truck tires, especially wide-base singles, possess rather low levels of vertical stiffness such that roll stability is reduced.

11) Sloshing liquid loads serve to contribute both static and dynamic effects which degrade roll stability.

12) Laterally-offset solid loads, as occur either due to in-transit shifting of the load or simply due to an inherently asymmetric payload serves to directly reduce the effective "half-track dimension."

In transient maneuvers, such as a lane change, the onset of rollover is not as directly related to the simple summation of moments in the roll direction, but will also depend on the dynamics of the vehicle in the maneuver. The dynamics impact on the amplitude and duration of the lateral acceleration exposure, and determine whether roll energy may have already been built up by preceding portions of the maneuver.

The rearward amplification phenomenon (see Section 2.2) is the most significant of the vehicle's dynamic performance properties that interact with the rollover process. As implied by the name, "rearward amplification," the severity of the maneuver executed at the front of the vehicle in response to driver actions, is altered in intensity at points further rearward in the vehicle or combination. With tractor-semitrailers, an attenuation occurs such that the driver can successfully operate the tractor for brief intervals at lateral acceleration levels beyond the rollover threshold of the combination. In the case of doubles combinations, however, rearward amplification exposes the rear trailer to lateral acceleration levels greater than those experienced by the tractor [3]. The presence of rearward amplification reduces the effective maneuvering level that the driver can execute without causing rollover [4].

Outboard offtracking (see Section 2.2) is a second form of dynamic performance that may potentially compound the risk of rollover. In the critical situation of high speed turning at high levels of lateral acceleration, the rear axles in a vehicle train may move out beyond the path steered by the driver at the front of the tractor. This increases the potential that the axles may encounter conditions conducive to rollover. Impacts with curbs or low barriers will produce an impulse of lateral acceleration that may be sufficient to trip the vehicle to an irrecoverable roll angle. The tires may drop off of a pavement edge adding to the effective cross-slope experienced by the trailer. Or, the tires may encounter gravel or other material reducing their cornering traction and allowing the trailer to swing to a higher slip angle condition.

To what extent the driver can sense imminent rollover in transient situations and modify the vehicle path to prevent its occurrence is not well established. With straight trucks and tractor-semitrailers there is some possibility that the driver can sense imminent rollover and perhaps intercede by a steering correction. The lack of knowlege in this area may be somewhat obscured by the fact that many of these vehicles become yaw unstable before rollover, impeding the driver from taking appropriate action. Certainly, in the case of the second trailer of a doubles combination, the driver cannot avoid a rollover by his steering actions because of his inability to feel what the trailer is doing, and the delays between steer inputs and responses at the end of the train. By and large, the base of knowledge at the fundamental level of driver lateral acceleration demand in the operation of heavy duty vehicles is too deficient to support any understanding of the driver/vehicle combination in rollover accident causation.

Thus, in transient maneuvers an absolute rollover threshold cannot be defined as simply as for the static case. It must be defined in terms of the peak levels achievable in specific maneuvering situations. Although the static threshold is logically a relative measure of a truck's propensities for rollover accidents, in any transient maneuver the dynamics of the vehicle and the exact nature of the maneuver will influence whether a rollover actually occurs.

2.1.2 Significance. Rollovers constitute a very visible and serious type of commercial vehicle accident. Of the accidents reported each year to the BMCS, approximately one-third involve rollover. In the years 1973-1976, these accidents are responsible for approximately 17 percent of the deaths, 33 percent of the injuries and 30 percent of the property damage reported. The UMTRI data base for trucks involved in fatal accidents covering 1980-82 indicates rollover in 17 percent of all fatal accidents, and 40 percent of all truck single vehicle accidents. Among those single vehicle accidents, rollover is the first event 23 percent of the time, and it is rated as the most harmful event in 30 percent of the cases. It is estimated that there are 1000 tractor-semitrailer rollovers in the U.S. each year, and perhaps 2000 total for the medium-heavy truck classes. Rollover of the second trailer is the most frequent event (60 to 75 percent) in rollovers involving doubles combinations.

Although two generalized vehicle performance properties—static rollover threshold and dynamic behavior—are theoretically linked to rollover occurrence, the static rollover threshold has been found to be closely linked with rollover accident frequency in single vehicle accidents of tractor-semitrailers [5]. The relationship, shown in Figure 2.1.3, was developed by estimating rollover thresholds for vehicles in the BMCS accident records based on the reported loading condition at the time of the accident. Suitable accident data files have not been available to determine whether this same relationship holds for straight trucks, or for doubles or triples. (For example, the available statistics on light truck rollover accidents show a much higher involvement.) Thus, there remains the technical question of whether the static rollover threshold alone is a suitable measure of rollover propensity for different vehicle classes, and what the quantitative relationship might be between this property and rollover frequency.

2.1.3 Potential for Improvement. A number of paths are available by which to improve rollover threshold and dynamic behavior of modern trucks as a way to reduce this type of accident. The most productive means to reduce rollover thresholds are by control of center-of-gravity height and use of wider vehicles. The wider (102-inch) vehicles will have a tendency to reduce loading heights as well as permitting wider track and suspension spreads. It has been estimated that reductions up to 35 percent in rollover might be possible with tractor-semitrailers operating with "medium-density freight" [6]. Smaller, but significant, reductions are also possible by optimizing suspension system properties with an eye toward maximizing compatibility of tractors and trailers. The mechanical properties of vehicles affecting the static rollover threshold are sufficiently well understood that it is possible to improve performance at the initial design stage. Tilt-table test methods have been devised and are used in Canada, Europe,. and Australia to experimentally quantify the static rollover thresholds of heavy duty vehicles.

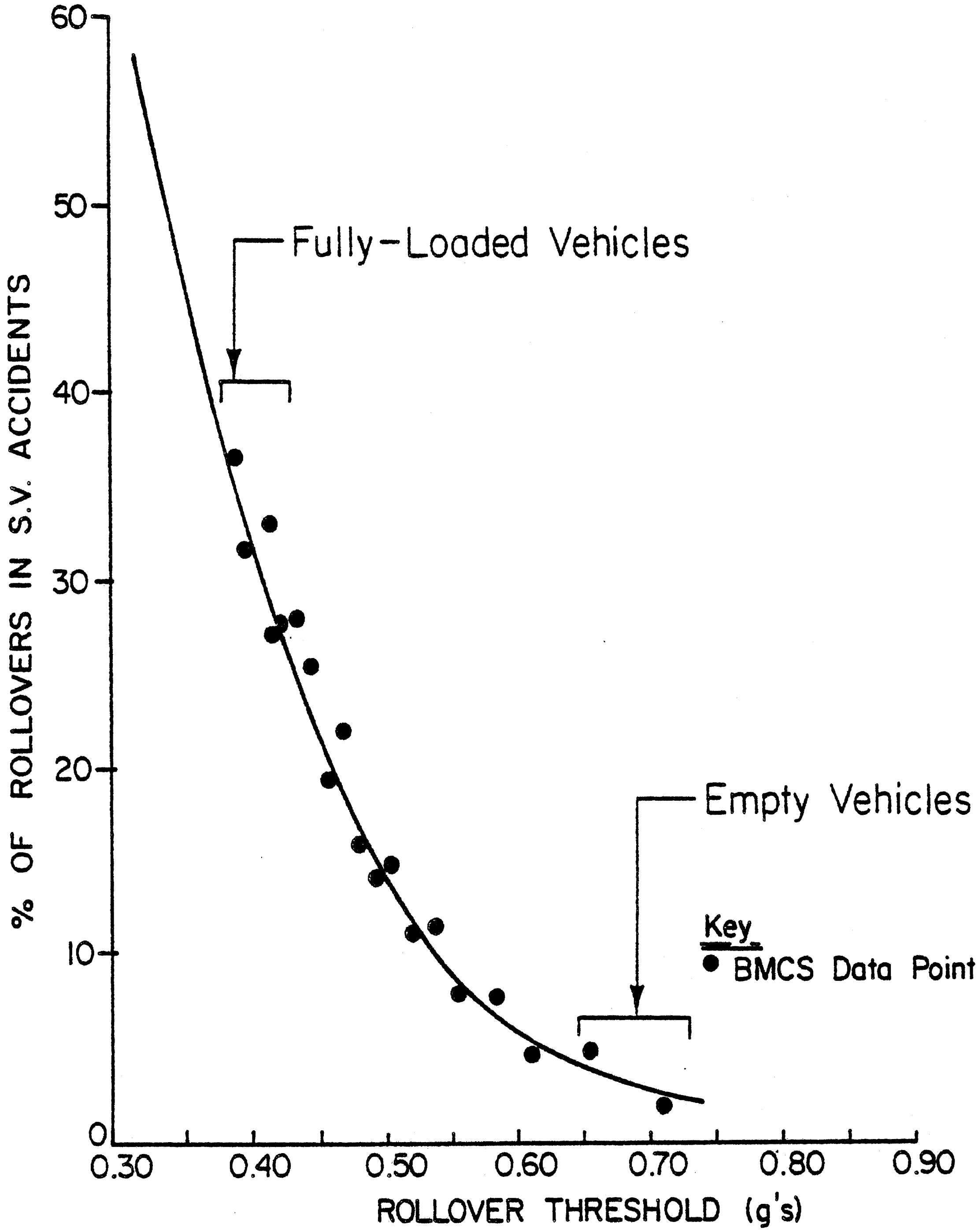


Figure 2.1.3 Percent of single-vehicle accidents in which rollover occurs as a function of the vehicle's inherent rollover threshold, in g's.

To the extent that rearward amplification contributes to rollover with doubles combinations, improvements are possible by better control of this dynamic mode. In recent research at UMTRI it has been found that the rearward amplification factors are characteristically on the order of 2 to 2.5 with typical "Western" doubles. With improved dolly designs, rearward amplification can be readily reduced to the order of 1.5.

Each of these changes involve some penalty to the trucking industry, either in higher initial cost or weight. Wider vehicles and monitoring the center-of-gravity height of loaded vehicles will add to the difficulty and expense of general operations. Suspension improvements for rollover may incur penalties in ride and/or cargo damage. By and large, the full implications of the changes that will improve rollover accident experience are not well known.

References

1. Winkler, C. B., Fancher, P.S., and MacAdam, C.C., "Parametric Analysis of Heavy Duty Trunk Dynamic Stability," Final Report Contract No. DTNH 22-80-C-07344, University of Michigan Transportation Research Institute Report UMTRI-83-13, March, 1983.

2. Ervin, R. D., "The Influence of Size and Weight Variables on the Roll Stability of Heavy Duty Trucks," SAE Paper No. 831163, 1983, 26 pp.

3. Nordstrom, O. and Strandberg, L., "The Dynamic Stability of Heavy Vehicle Combinations," Report No. 67A, National Swedish road and Traffic Research Institute, 1975.

4. Ervin, R. D., et al, "Ad Hoc Study of Certain Safety-Related Aspects of Double-Bottom Tankers," Final Report to Michigan Department of State Police, Office of Highway Safety Planning, Contract No. MPA-78-002A, Highway Safety Research Insitute, University of Michigan, May 7, 1978.

5. Ervin, R. D., et al, "Future Configurations of Tank Vehicles Hauling Flammable Liquids in Michigan," Final Report, Highway Safety Research Institute, University of Michigan, Report No. UM-HSRI-80-73, December 1980.

6. Gillespie, T. D., and Ervin, R. D., "Comparative Study of Vehicle Roll Stability," Final Report, University of Michigan Transportation Research Institute, Report No. UMTRI-83-25, May 1983.

2.2 Trailing Fidelity

In the operation of combination vehicles (i.e., tractors pulling one or more trailer units), it would be generally desirable for the tires of each of the trailing units to track the same path as the tires of the tractor under all operating conditions (and, indeed, for the rear tires of the tractor or truck to track the front tires). This would ensure (1) that the swept path of the vehicle was practically minimal, and (2) that each of the trailers would experience the same severity of maneuver as did the tractor, and that, in general, the driver would be in control of trailer behavior to the same extent that he was in control of tractor behavior.

"Trailing fidelity" refers to this ability of trailers to precisely follow the tractor. Unfortunately, the basic properties of conventional commercial vehicles result in trailing fidelity that is often less than desirable. Three performance areas are of concern, viz.:

- Low-speed offtracking

- High-speed offtracking

- Rearward amplification

Offtracking refers to the lateral dimension by which trailing axles fail to precisely track preceding axles during steady-turning maneuvers. Rearward amplification refers to failure of trailers to precisely follow the towing vehicle's path during dynamic turning maneuvers, such as rapid lane changes.

These three performance properties are related, not only by definition (trailing fidelity), but by parameteric sensitivity. That is, several individual vehicle parameters (e.g., wheelbase) have a strong influence on each of these performance properties. Unfortunately, the changes in vehicle parameters, which would improve one performance area, might well degrade another. Accordingly, it is likely that performance standards for these three areas should not be developed separately, but rather in conjunction, such that these conflicts are clearly recognized.

2.2.1 Mechanics of Trailing Fidelity. Low-speed offtracking. When traveling at low speed, all vehicles (who use steering front axles and non-steering rear axles) exhibit inboard offtracking in low-speed cornering. This is true of cars, single-unit trucks and combination vehicles. Recognizing that, at low speed, each tire travels forward in just the direction it is pointed, it is straightforward to show that each axle of the vehicle subtends a curved path whose radius is smaller than the radius of the path of the preceding axle. Low-speed offtracking is illustrated in Figure 2.2.1.

The extent to which a commercial vehicle will offtrack at low speed is strongly related to its length, or wheelbase. However, offtracking is reduced by the addition of articulation joints. Thus, for example, as shown in Figure 2.2.2, the low-speed offtracking of a doubles combination vehicle composed of two 28' trailers is generally less than that of a single-trailer vehicle using a 45' trailer, even though the double is considerably longer overall. This is one of the attractive features involved in the growing popularity of doubles.

These properties of conventional vehicles, viz., longitudinal layout geometry (wheelbases and hitch locations) and the number of articulation points, are well understood and are known to be the dominant influences on offtracking behavior [1-5]. Other properties which have lesser influences include the use of dual tires and tandem-axle suspensions, tire stiffness properties, and tire-to-road friction levels [4]. Further, the transient offtracking behavior (which occurs as the vehicle enters and/or exits a steady turn) is well understood [5].

Low-speed offtracking may also be strongly influenced by steering the wheels of trailer or dolly axles. This unconventional approach can completely eliminate low-speed offtracking. Largely because of its cost, however, it is generally only employed in specialized, exceptionally long vehicles, whose offtracking behavior would be categorically unacceptable otherwise. The new "B-dolly" concept, finding limited use in doubles applications, can improve low-speed offtracking also, albeit in a vehicle whose low speed offtracking is already relatively good. (B-dollies will be considered further in the rearward amplification discussion.)

High-speed offtracking. While low-speed offtracking is characterized by each axle of the vehicle tracking a smaller radius than the axle preceding it, high-speed offtracking has the opposite quality. Generally, it can be expected that commercial vehicles will exhibit outboard, rather than inboard, offtracking at highway speeds.

As shown in Figure 2.2.3, when cornering at speed, each tire does not travel in precisely the direction it is pointed. Rather, in order to develop the necessary cornering forces, each tire operates at some so-called slip angle. The level of slip angle at each tire depends on tire properties, tire loading, and the severity of the maneuever (i.e., the level of

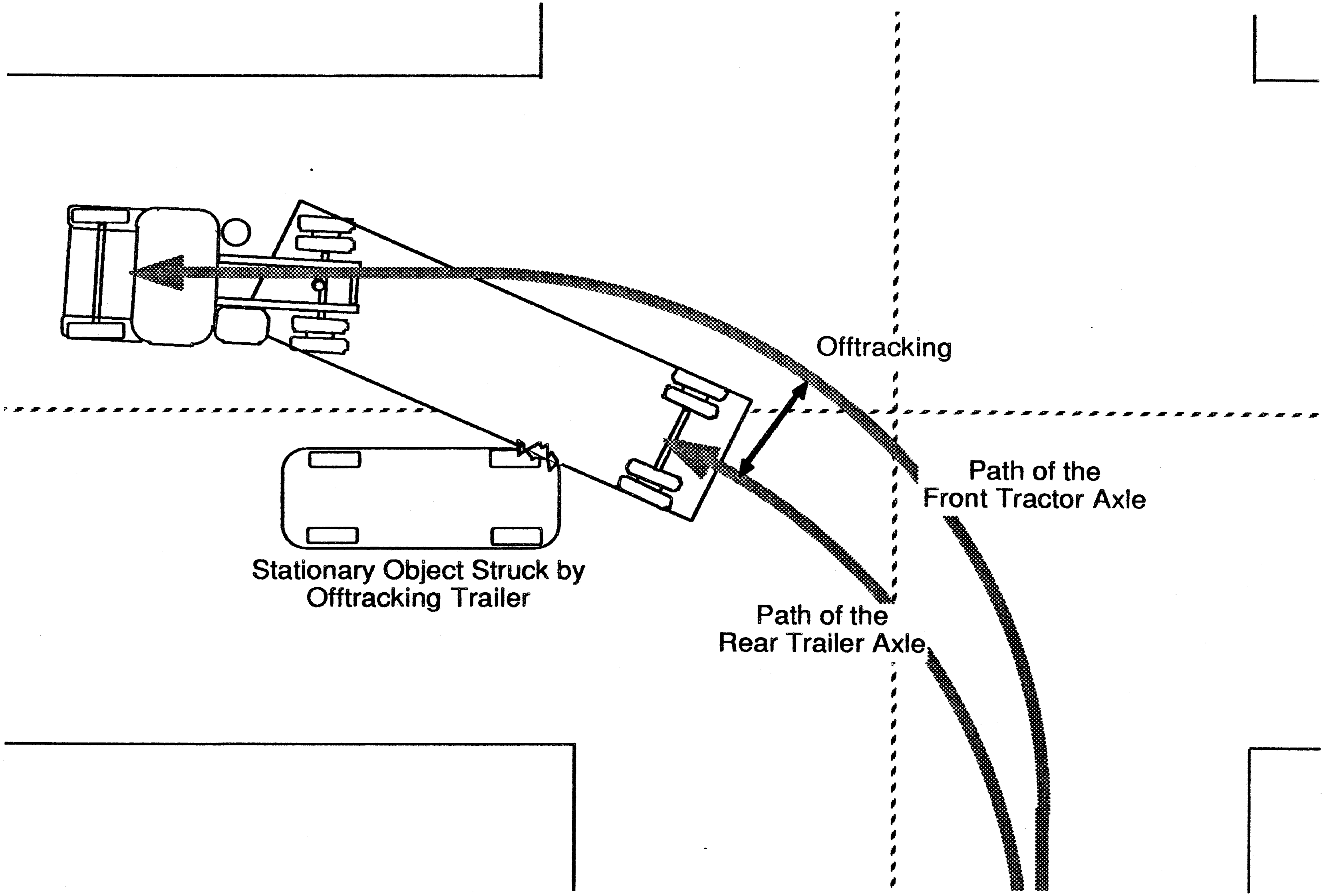


Figure 2.2.1. In low-speed offtracking, each axle tracks inboard of the preceding axle. A typical accident scenerio involves the trailer, side-swiping a stationary object.

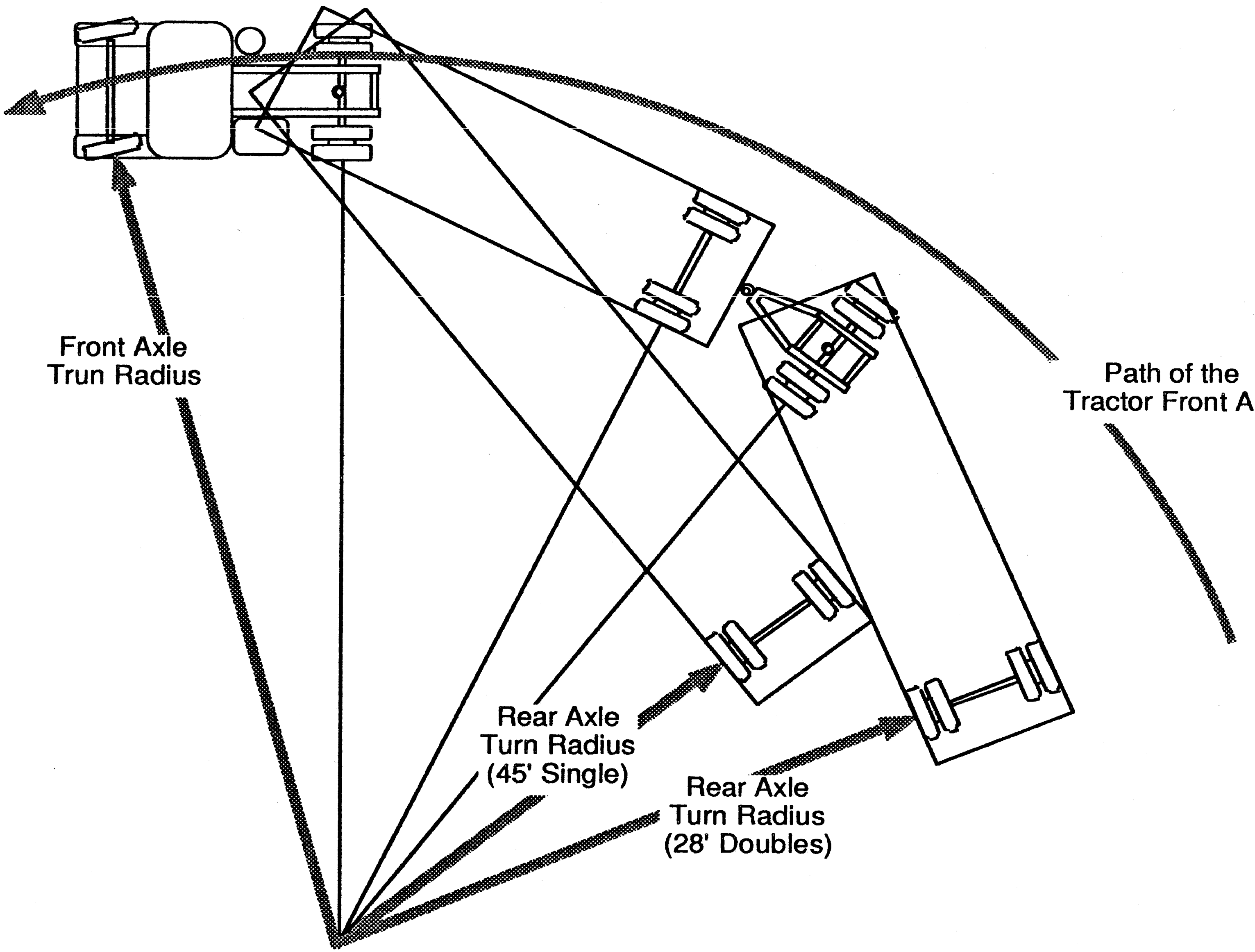


Figure 2.2.2. The lowspeed offtracking of 28 foot twin trailers is less than the lowspeed offtracking of a single, 45 foot trailer.

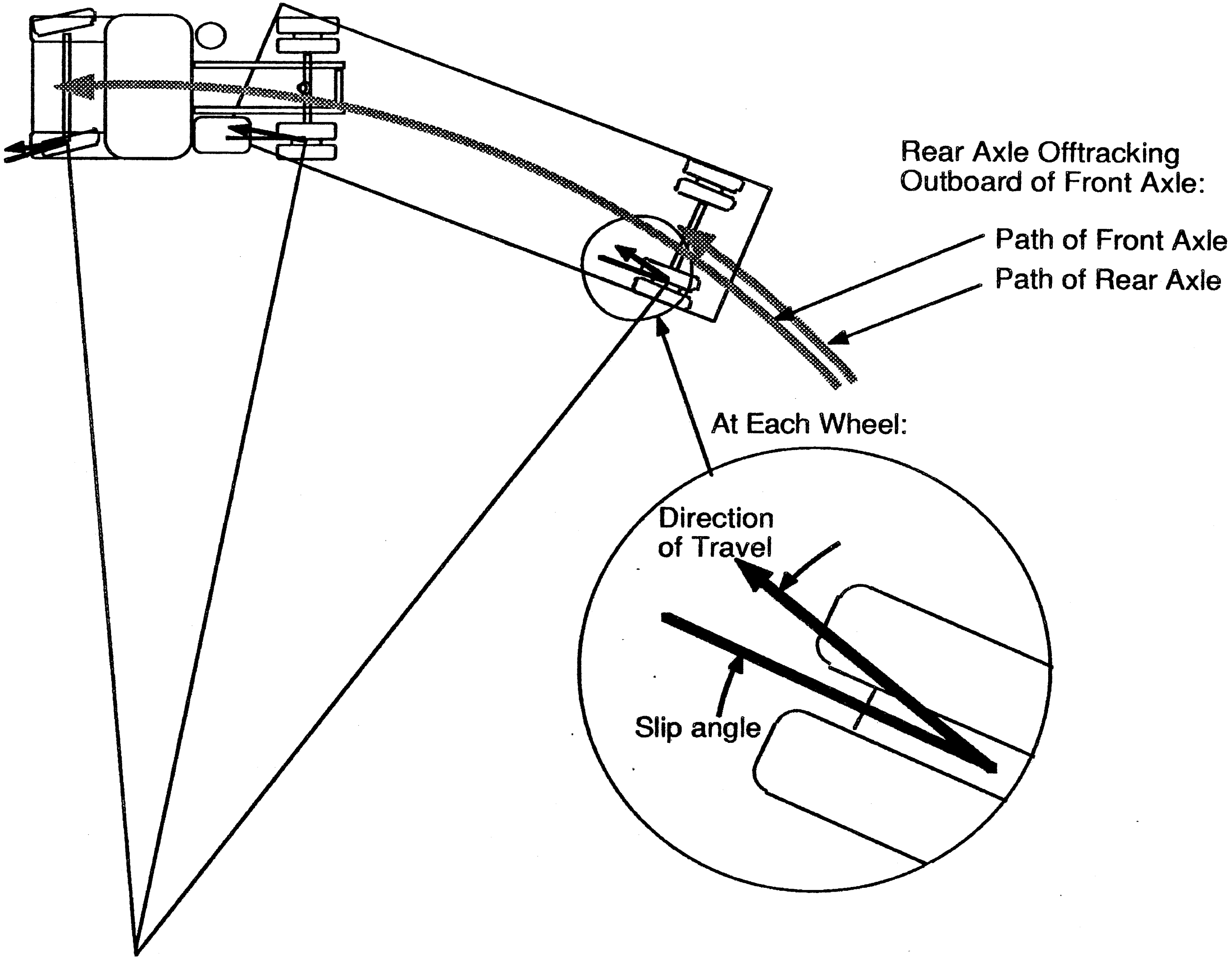


Figure 2.2.3. When cornering at speed, trailers may offtrack outboard of the tractor if the tire slip angles are large enough.

required cornering force at that tire). When slip angles are large enough, rear axles may offtrack outboard of the front axles of the vehicle.

The physical mechanisms involved in high-speed offtracking are well understood, and mathematical analyses are well developed [6]. High-speed offtracking is essentialy composed of inboard, low-speed offtracking plus the out-board offtracking induced by slip angle. The latter, outboard component is large at higher speeds for longer vehicles with lower cornering stiffness tires. Note, also, that vehicle properties (such as more articulation joints) which lessen low-speed, inboard offtracking, will, by the same token, aggravate outboard, high-speed offtracking. Thus, inboard, low-speed offtracking and outboard, high-speed offtracking are problems whose solutions may be in fundamental opposition.

Rearward amplification. Rearward amplification refers to the trailing fidelity of articulated vehicles during dynamic maneuvers. Specifically, it has been found that in transient maneuvers, the rear unit of multi-articulated vehicles may well experience a maximum lateral acceleration which substantially exceeds the maximum acceleration of the lead unit of the vehicle. In general, lateral acceleration of each unit may be expected to increase over that of the preceding unit; thus the term, rearward amplification. Technically, rearward amplification of a multi-trailer vehicle is the ratio of the peak lateral acceleration of the last trailer to the peak lateral acceleration of the tractor, measured in a sinusoidal steer (lane change) maneuver. Figure 2.2.4 attempts to illustrate the so-called "cracking-the-whip" type of behavior which is characteristic of vehicles with large rearward amplification.

Rearward amplification is a frequency-sensitive phenomenon, tending to be more pronounced in maneuvers where steering has an unusually high frequency content, such as rapid, evasive lane-change maneuvers. This is so because these vehicles are multi-degree-of-freedom mechanical systems, characterized by several, oscillatory dynamic modes, each with their own natural frequency. When such a system is excited by inputs whose frequencies are near the natural frequencies of one or more lightly damped modes, strong, resonant-like responses occur. The natural frequencies of the lightly damped modes of these vehicles tend to be higher than the frequencies used in normal driving, but low enough to be attained in emergency, evasive maneuvers.

In recent years, substantial effort has been given to analysis of rearward amplification [7-21]. It is understood that individual elements of multi-articulated vehicles

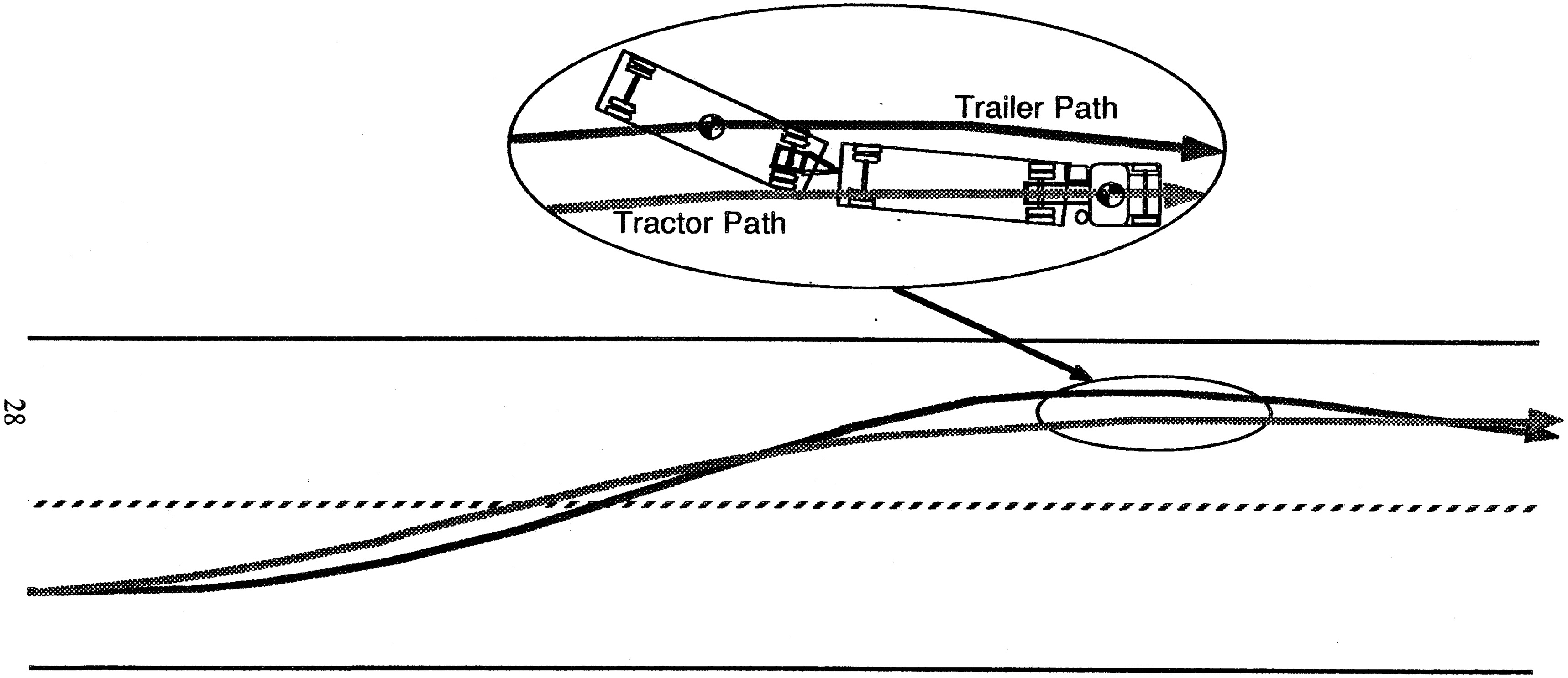


Figure 2.2.4. In a rapid lane change maneuver, rearward amplification results in "crack-the-whip" action of the rear trailer, sometimes resulting in rear trailer rollover.

can be seen as having their own rearward amplification properties. In this line of analysis, the tractor-semitrailer is considered as a unit, as are each full trailer. (This is possible due to the relatively small pintle hitch forces required to produce steering in the "wagon tongue" steering mechanisms commonly used. This physical fact results in a so-called mathematical "decoupling" at each pintle hitch joint, allowing separate analysis of each unit.) Separate rearward amplification factors can be calculated for each unit. For the tractor-semitrailer, amplification from the tractor center of gravity (c.g.) to the pintle hitch on the rear of the trailer is found. For each full trailer, two factors are found. The first concerns amplification from the tow-bar hitch point back to the c.g., and the second concerns amplification from the c.g. back to the pintle hitch towing the next trailer. The total rearward amplification of the vehicle is the product obtained by multiplying all these individual amplification factors.

These analyses have shown that, for the conventional multi-trailer vehicle, the most important vehicle properties relating to rearward amplification are (1) tire cornering stiffness, (2) vehicle wheelbase, and (3) pintle hitch location in the towing trailer. Stiffer tires, longer wheelbases, and more forward locations for the pintle hitch all reduce rearward amplification. (Somewhat surprisingly, tow-bar length of the full trailers is now known to be relatively unimportant.) Thus, doubles, composed of two short trailers, generally show rather high, overall rearward amplification, as do trucks towing short, full trailers, particularly when the truck has a large rear overhang to the pintle hitch. Addition of other full trailers, as in triples, further aggravates the problem. Since "tuning" among the various elements of the vehicle is involved, vehicles with multiple, identical trailers can generally be expected to have greater amplification.

Another fact of great importance is that rearward amplification is strongly related to the nature of the trailer-to-trailer hitching mechanism. The so-called A-dolly has long been the industry staple. Figure 2.2.5 illustrates that an "A-train" is composed of a tractor-semitrailer hauling one or more full trailers which are made up of a semitrailer and A-dolly. The use of the A-dolly produces full trailers using very simple, "wagon tongue" steering.

Analytically, the A-dolly results in two additional articulation joints (the pintle hitch joint and the fifth wheel joint) for each trailer added to the train. The elimination of the pintle hitch articulation joint can substantially reduce rearward amplification. This can be accomplished by installing a fifth wheel on an extended frame of the first semi, as in Figure 2.2.6. The result is the so-called B-train whose configuration is basically that of a tractor-semitrailer-semitrailer.

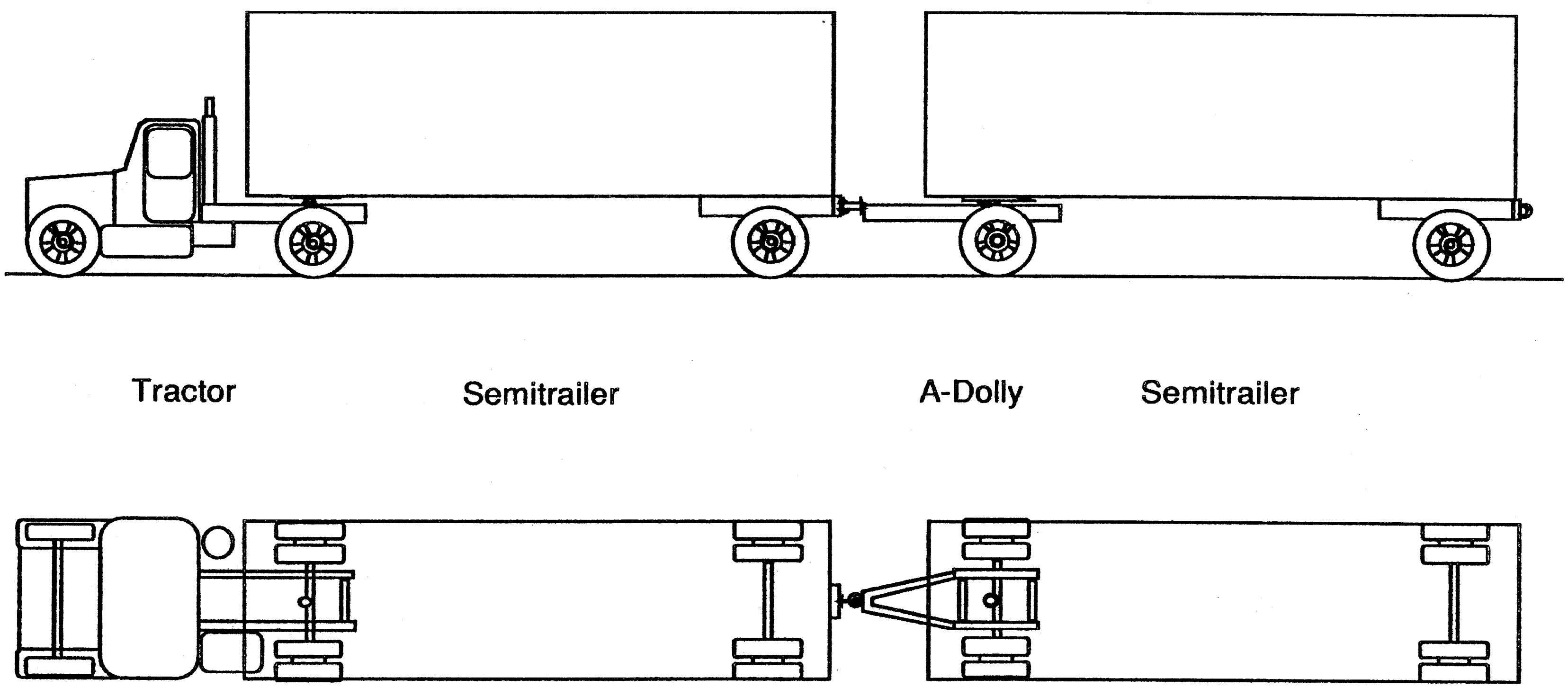


Figure 2.2.5. An A-train is composed of a tractor-semitrailer towing one or more full trailers made of an A-dolly and semitrailer.

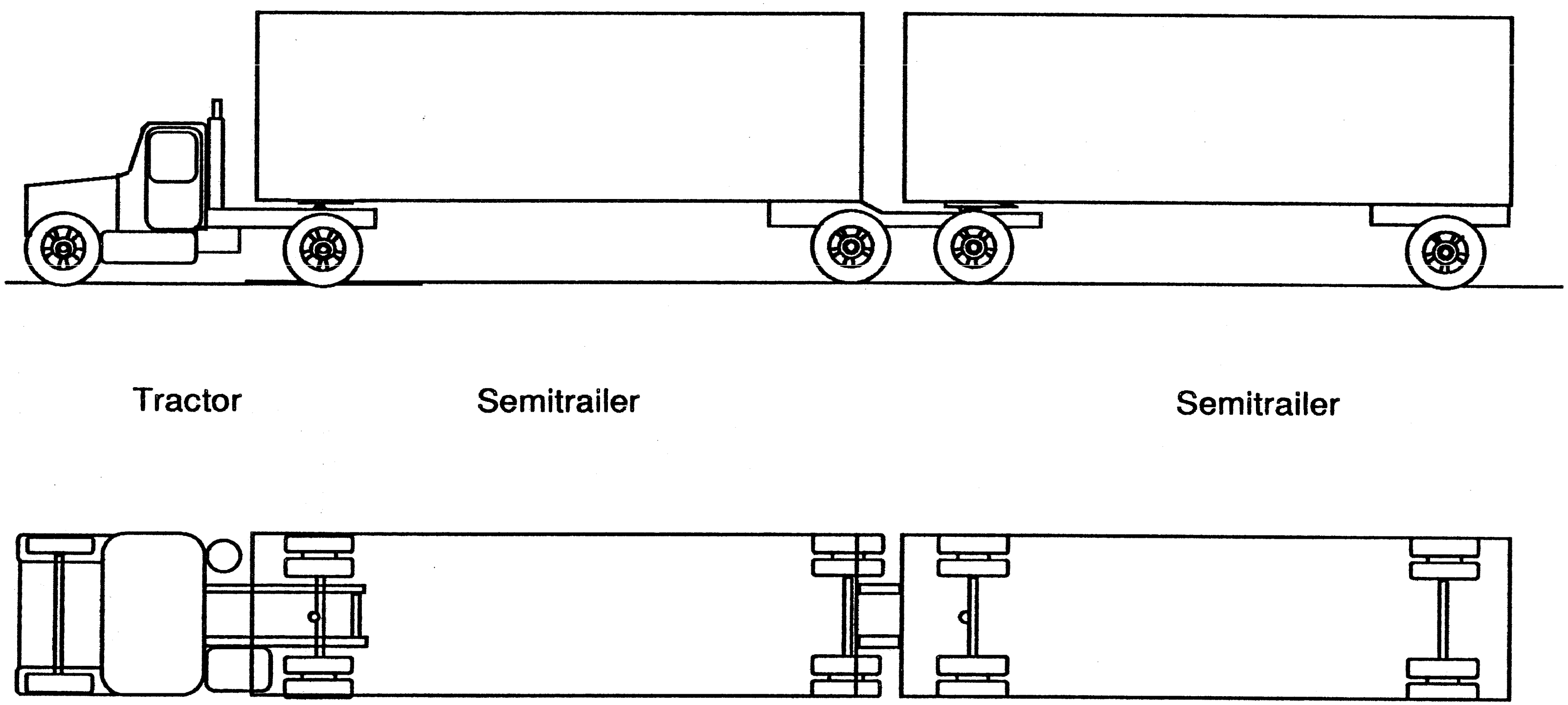


Figure 2.2.6. A B-train is composed of a tractor towing two or more semitrailers. The towing trailers have an extended frame with 5th wheel for attaching the next trailer made of an B-dolly and semitrailer.

A more popular variation on the theme uses a B-dolly in making up a C-train. Shown in Figure 2.2.7, this dolly uses two pintle hitches to eliminate dolly steering. Usually, the dolly is equipped with a "self-steering" axle. The device allows the dolly tires to steer by caster, but with some centering mechanism applied. The goal is to allow enough free steering to reduce tire wear and objectionable frame stresses, but to supply enough steering resistance to provide dynamic stability [22-24].

Other innovative dolly concepts are known and have seen limited exposure. These include the "four-bar link dolly," the "linked articulation concept," and a controlled steering dolly [24].

All these innovative hitching concepts can improve dynamic performance, but each has drawbacks which tend to severely restrict their use in the United States. After all, the A-dolly is a remarkably simple, cheap, light, low-maintainence, highly-practical device, with virtually no drawbacks other than that it contributes to the rearward amplification phenomenon. Each of the other available dolly concepts exacts penalties of initial cost, weight, maintenance, and operational difficulties. As a result, the A-dolly remains as virtually the only such device used in the United States.

Recent research [24] has revealed a property of the rearward amplification/rear trailer rollover problem which was previously unrecognized, and is, as yet, not fully understood. As noted, rearward amplification is a frequency-sensitive matter, such that the lateral acceleration of the rear trailer can be expected to be most severe when steering activity takes place at a particular frequency. While analysis and testing show this to hold true, it is also found that, in these highly dynamic maneuvers, rear trailer rollover is not necessarily most likely to occur in these "most severe" maneuvers, but at maneuvers of slightly lower frequency. Apparently, there are also important influences associated with frequency tuning with the trailer roll motions as well as yaw (steering) motions.

2.2.2 Significance. Low-speed offtracking. Figure 2.2.1 illustrated low-speed offtracking for a tractor-semitrailer, and showed one mechanism by which this inboard offtracking behavior is known to be the cause of some property damage accidents. Particularly in urban environs, the trailer of combination vehicles may "side-swipe" stationary objects which have already been cleared by the tractor.

Low-speed offtracking also causes maneuverablitiy problems and traffic flow restriction problems. As shown in Figure 2.2.8, drivers who are well aware of the offtracking properties of their vehicles, may swing the tractor very wide through urban

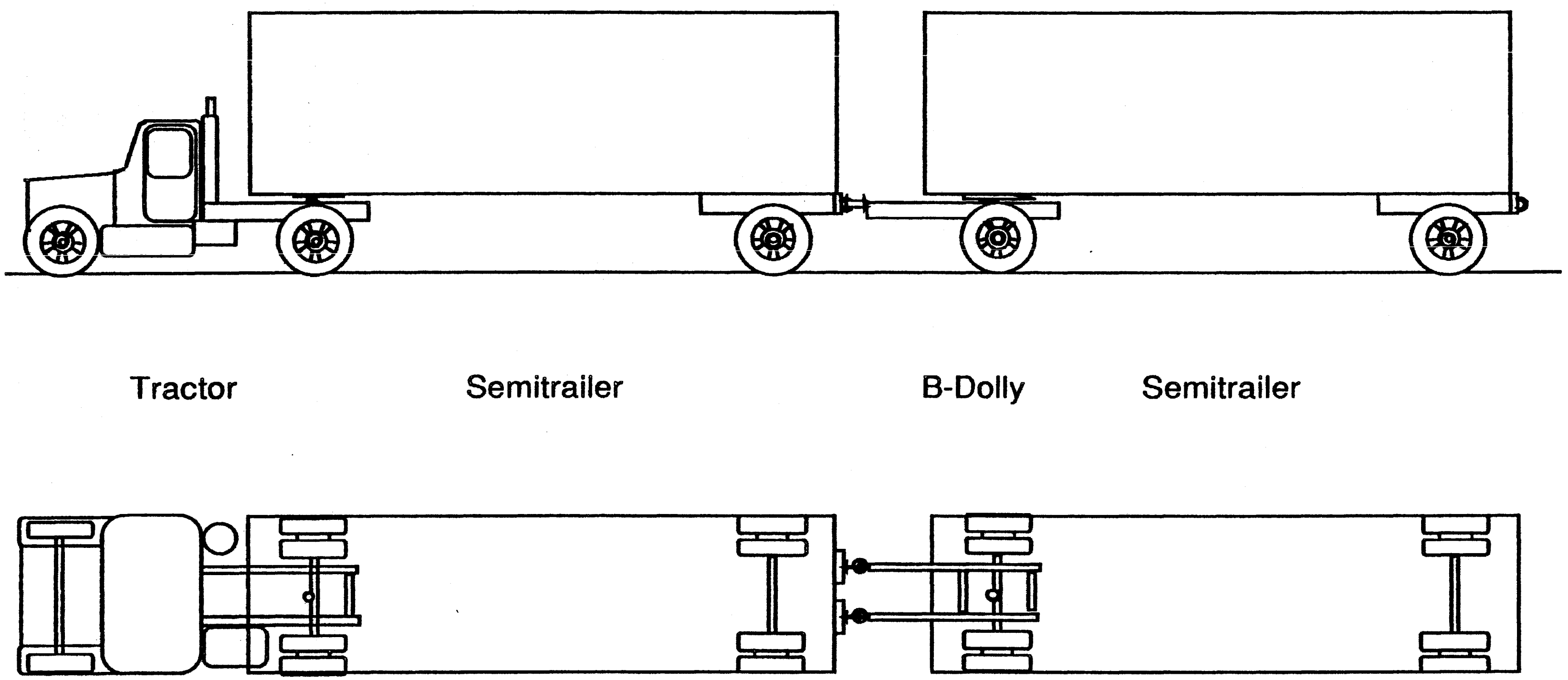


Figure 2.2.7. A C-train is composed of a tractor-semitrailer towing one or more full trailers made of an B-dolly and semitrailer.

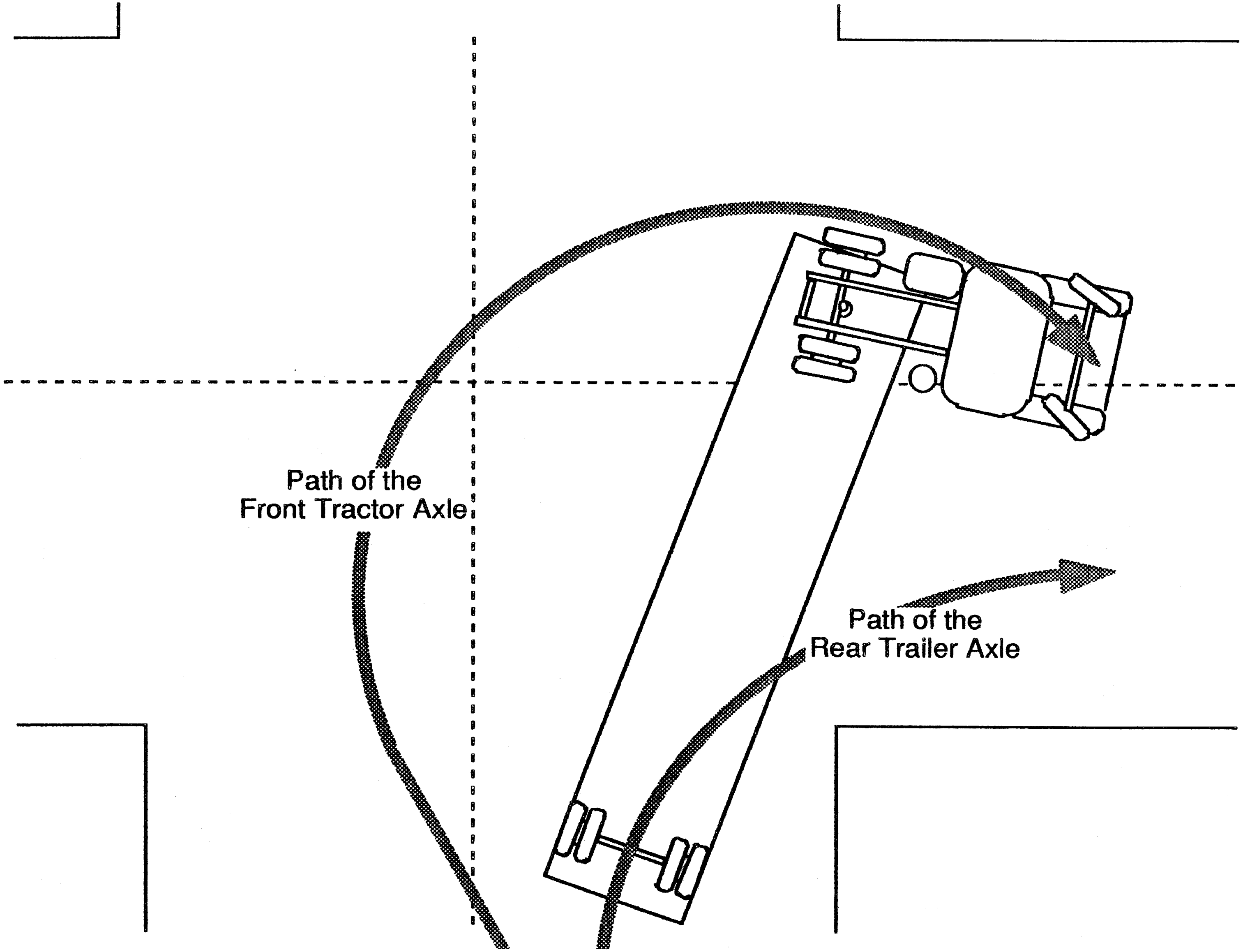


Figure 2.2.8 To avoid a low speed offtracking accident, the driver must swing the tractor very wide through urban turns, intruding on other traffic lanes.

corners to avoid trailer accidents. If the tractor protrudes into the right-of-way of oncoming vehicles, traffic flow may be disrupted. In extreme examples, there may simply not be enough space for the vehicle to maneuver.

Because of the lack of accident data, it is not clear, at this time, whether low-speed offtracking is currently a safety problem of sufficient magnitude to warrant rule-making as a remedial action. However, limited data in the public domain [26] suggests that long, single trailer combinations experience more "side-swipe" accidents than do doubles composed of two shorter trailers. This data would tend to imply that the larger, low-speed offtracking of the single was the cause of accidents. Of course, low-speed offtracking accidents can be expected to be relatively low-severity events.

High-speed offtracking. Outboard offtracking at speed is known to be the cause of a number of commercial vehicle accidents. The accident scenerio generally involves rollover of the (last) trailer in a high-speed turn such as is encountered at highway entrance and exit ramps. If a curb is present on the outboard side, trailer tires striking the curb as a result of outboard offtracking may provide the necessary impetus to cause rollover.

Again, a lack of accident data leaves the overall, safety significance of high-speed offtracking in some doubt. Clearly, individual accidents are expected to be more severe, economically and in terms of injury and death, than are low-speed offtracking accidents. The numbers of accidents which may be related to high-speed offtracking are, however, unknown.

Rearward amplification. The most serious safety concern related to rearward amplification is trailer rollover accidents. In addition, the swaying rear trailer may dangerously intrude into adjacent traffic lanes.

Rearward amplification is one vehicle property which is rather identifiable as a causative factor in the accident record. The physics suggest that accidents in which the rear trailer rolls over and all other units of the vehicle remain standing have a very high likelyhood of being associated with rearward amplification. Accordingly, the accident record can be examined for an over-representation of rear trailer rollover accidents as a way of gaging the safety importance of rearward amplification. Heath [25], of the California Highway Patrol has found that, amoung tankers, the last trailer of doubles and the full trailer of truck-full trailer combinations are particularly susceptable to rollover. Two-thirds of the doubles rollover accidents were rear-trailer-only rollovers, and more than half of the truck-trailer rollovers were trailer-only rollovers. Accident data on the Consolidated

Freightways fleet, revealed in litigation [26], tended to show that while doubles do not have many more accidents than tractor-semitrailer combinations, many more of the doubles accidents involve rollovers and some 60 percent of the doubles rollover accidents are rear-trailer-only type. These data then, indicate that rearward amplification plays an important roll in the doubles accident picture, tending to increase the cost and severity of the accidents which these vehicles have.

2.2.3 Potential for Improvement. Each of the three individual elements of trailing fidelity (low-speed offtracking, high-speed offtracking, and rearward amplification) has several, identified mechanisms by which that particular performance property could be improved. Significantly, however, vehicle changes which improve one performance area may degrade another. This conflict is, perhaps, the most serious restiction to improving any of the three performance ranges. To the extent that compromises are necessary, serious evaluation of current accident experience and costs are called for to rationally guide the decision making process.

With these coments in mind, each of the three areas will now be considered.

Low-speed offtracking. In one sense, the expanding use of doubles composed of short wheelbase trailers, in favor of singles using longer trailers, could be seen as an activity which is currently reducing the low-speed offtracking problem. That is, the use of vehicles which are composed of shorter wheelbase units, even if the overall vehicle length is longer, is one method of improving lowspeed offtracking. Optimizing the location of axles and hitch points can also serve to reduce low-speed offtracking. These geometric mechanisms, however, tend to conflict directly with both high-speed offtracking and rearward amplification goals, especially when applied to the conventional A-train vehicle.

Controlled steering of rearward axles (dolly and trailer axles) is a potential, albeit expensive, means for improving low-speed offtracking. If economic incentives for improved productivity were sufficient, such approaches could be used to meet offtracking restraints with, for example, longer vehicles than are currently common.

High-speed offtracking. Generally speaking, the same geometric properties which influence low-speed offtracking also influence high-speed offtracking, but the polarity of desirable changes is opposite between the two.

Tire properties also influence high-speed offtracking. Use of only the higher cornering stiffness tires (steel-belted radials, for example) could potentially reduce the numbers of high-speed offtracking accidents. Significantly, higher cornering stiffness is an attractive feature for virtually all aspects of vehicle directional performance.

Again, the rather advanced notion of controlled steering of rear axles could be used to improve performance. If sufficiently sophisticated control logic and mechanisms were used, such systems could certainly be made compatible with the low-speed offtracking performance goals.

Rearward amplification. Rearward amplification performance of doubles can be improved by geometric changes, particularly longer wheel-bases and improved hitch locations. These changes tend to be in conflict with those that are advantageous to reduce low-speed offtracking.

Rearward amplification is quite sensitive to tire cornering stiffness. The use of only the highest cornering-stiffness tires could be expected to make a significant impact on improving the performance of the fleet with no expectation of degrading other safety performance areas.

Innovative dolly concepts are known to be most effective in reducing rearward amplification. Some of these concepts are in conflict with low-speed offtracking goals, but others can be implemented with virtually no change in offtracking behavior.

References

1. "Turning Ability and Offtracking--Motor Vehicles." SAE J695b, SAE Recommended Practice, Society of Auto. Engrs. Handbook, 1981.

2. "Offtracking Characteristics of Trucks and Truck Combinations." Western Highway Institute, February 1970.

3. Sayers, M.W. "Vehicle Off-Tracking Models." Proceedings of a Symposium on Geometric Design for Large Trucks, Denver, August 5-7, 1985.

4. Morrison, W.R.B. "A Swept Path Model Which Includes Tyre Mechanics." Proceedings, Sixth Conference, Australian Road Research Board, Vol. 6, Part 1, Canberra, 1972.

5. Jindra, F. "Off-Tracking of Tractor Trailer Combinations." Automobile Engineer, March 1963, pp. 96-101.

6. Bernard, J.E. and Vanderploeg, M. "Static and Dynamic Offtracking of Articulated Vehicles." SAE Paper No. 800151, 1980.

7. Jindra, F. "Lateral Oscillations of Trailer Trains." Ingenieur-Archiv., XXXIII, 1964, p. 194.

8. Hazemoto, T. "Analysis of Lateral Stability for Doubles." SAE Paper No. 730688, June 1973.

9. Hales, F.D. "The Rigid Body Dynamics of Road Vehicle Trains." Proceedings, I.U.T.A.M. Symposium on the Dynamics of Vehicles on Roads and Tracks, Delft, August 1975, p. 131.

10. Jindra, F. "Offtracking of Tractor-Trailer Combinations." Automobile Engineer, March 1963, pp. 96-101.

11. Sharp, R.S. "The Steering Responses of Doubles." IAVSD Symposium, Berlin, September 1979.

12. Nordmark, S. and Nordstrom, O. "Lane Change Dynamics Versus Geometric Design of Truck and Full Trailer Combinations." Proceedings, XVI Int. Auto. Tech. Congr. FISITA, Tokyo, p. 1737.

13. Ervin, R.D., et al. "Ad Hoc Study of Certain Safety-Related Aspects of Double-Bottom Tankers." Final Rept., Highway Safety Res. Inst., Univ. of Mich., Rept. No. UM-HSRI-78-18, Sponsored by Mich. State Office of Highway Safety Planning, Cont. No. MPA-78-002A, May 7, 1978.

14. Mallikarjunarao, C. and Fancher, P.S. "Analysis of the Directional Response Characteristics of Double Tankers." SAE Paper No. 781064, December 1978.

15. Mallikarjunarao, C. and Segel, L. "A Study of the Directional and Roll Dynamics of Multiple-Articulated Vehicles." Proceedings, 7th IAVSD-IUTAM Symposium on Dynamics of Vehicles on Roads and Tracks, Cambridge, England, September 1981.

16. Ervin, R.D. and MacAdam, C.C. "The Dynamic Response of Multiply-Articulated Truck Combinations to Steering Input." SAE Paper No. 820973, August 1982.

17. Fancher, P.S. "The Transient Directional Response of Full Trailers." SAE Paper No. 821259, November 1982.

18. Winkler, C.B., Fancher, P.S., and MacAdam, C.C. "Parametric Analysis of Heavy-Duty Truck Dynamic Stability." Final Rept., Contract No. DTNH22-80-C-07344, Transp. Res. Inst., Univ. of Mich., Rept. No. UMTRI-83-13, March 1983.

19. Ervin, R.D., et al. "Influence of Size and Weight Variables on the Stability and Control Properties of Heavy Trucks." Final Rept., Contract No. FH-11-9577, Transp. Res. Inst., Univ. of Mich., Rept. No. UMTRI-83-10, March 1983.

20. Fancher, P.S. and Segel, L. "Offtracking Versus Stability and Dynamic Response of the Trackless Train." 8th IAVSD Symposium, Cambridge, Mass., August 15-19, 1983.

21. Ervin, R.D. "The Importance of Tire Cornering Properties to the Dynamic Behavior of Heavy-Duty Trucks." 127th Meeting of Rubber Div., Amer. Chem. Soc., Los Angeles, April 23-26, 1985.

22. Woodrooffe, J.H.F., Billing, J.R., and Nisonger, R.L. "Improved Stability and Handling of Truck Combinations with the Double Drawbar Dolly." SAE Paper No. 831162, August 1983.

23. Nisonger, R.L. and Ervin, R.D. "Dynamic Behavior of the B-Type Converter Dolly." Final Rept., Contract No. OSX82-00094, Transp. Res. Inst., Univ. of Mich., Rept. No. UMTRI-83-44, September 1983.

24. "Techniques for Improving the Dynamic Ability of Multi-Trailer Combination Vehicles." Contract No. DTFH61-84-C-00026, Transp. Res. Inst., Univ. of Mich. (Ongoing Project).

25. Heath, W.M. "California Tank Truck Accident Survey - February 1, 1980 to January 31, 1981." California Highway Patrol, Sacramento, December 1981.

26. Consolidated Freightways Corp. of Delaware vs. Larson, et al., Civil No. 81-1230 (M.A.PA., Filed October 27, 1981), Exhibits 1010 through 1024 and 1070 through 1094.

2.3 Directional Stability and Response to Steering Control

2.3.1 Mechanics. Research has shown that the ability of a truck (or a tractor-trailer combination) to respond to steering control in a stable and well-damped manner is governed by physical phenomena which are considerably more complex than the comparable phenomena associated with the motor car [1]. The same statement can be made with respect to vehicle motions which are created by disturbances other than a displacement of the steering wheel.

The complexity, noted above, derives, in part, from the wide variety of vehicle configurations used to transport cargoes for commercial purposes and, in part, from the very limited range of behavior in which the response of the vehicle system is linearly related to the magnitude of the driver's steering input or the magnitude of any disturbing force. Additionally, the dynamic behavior of truck systems is more highly variable relative to the behavior exhibited by the motor car, since truck systems are operated with a wide range of inertial weights, depending on their state of loading.

The dynamic behavior peculiar to highway vehicles derives primarily from the mechanical properties of the pneumatic tire. Specifically, the ability of the pneumatic tire to distort laterally causes motor vehicles to exhibit a turn response to steering (i.e., a curved path) whose magnitude is speed dependent and which may either grow or decrease as speed is increased. In the case of the motor car, the rate of growth (or decrease) of path curvature with speed (per unit steering input) tends to be independent of the forces (acting at tire-road contact) which cause the vehicle to traverse a curved path, provided these forces are less than 0.3 times the weight of the car. In the case of the heavy-duty truck, the relationship between path curvature and steering input tends to become nonlinear at side-force levels which are less than one-tenth the weight of the truck [2]. Even more important than this limited range of linear behavior, is the general tendency of heavy trucks to lose their initial stable response quality and become a potentially unstable dynamic system when the side forces acting on the tires increase to levels above that required to cause the vehicle to become a nonlinear system but below the levels required to cause a rollover [3,4,5]. If the speed of the truck exceeds a certain level, a disturbance or a driver steering action will cause path curvature to increase in a divergent manner, provided the driver takes no follow-up action to stabilize the vehicle's path [6]. Even when the speed is below the speed at which the truck becomes unstable, a driver has the seemingly difficult task of controlling a mechanical system which is characterized by long response times as well as being characterized by large levels of turning response per unit displacement of the steering wheel.

The extent to which these characteristics influence the ability of drivers to keep a truck on a desired path, or change to a new path in a controllable and stable manner, is not known at this time. Further, the experience derived from the design and development of the passenger car does not provide any clear guidance, since the passenger car tends to behave in a linear manner over the range of maneuvering levels encompassed in normal, routine driving. Additionally, the motor car, which is intended to be driven by ordinary drivers, is carefully designed to lose its ability to turn at higher acceleration levels before stability is lost and a spinout occurs.

2.3.2 Significance. The question arises as to whether this state of affairs has any bearing on the extent to which drivers lose control of their trucks. Clearly, the accident record does not provide unambiguous evidence that truck drivers--a supposedly select, professional group--experience control difficulties in excess of the difficulties encountered by the motor car driving population. Nevertheless, it is reasonable to hypothesize that, since control problems arise primarily when the truck is required to perform a maneuver that is more severe than that experienced in everyday, routine driving, drivers do not have adequate opportunity to learn how to react properly under these conditions. This state of affairs suggests that the steering controllability characteristics of the heavy-truck population may be lacking so as to constitute a significant factor in the accident-causation process.

2.3.3 Potential for Improvement. The physics of truck response to steering is well understood, but the extent to which truck directional control and stability makes unreasonable demands upon driver skill is not. Research is required primarily to address the human factors aspects of the problem and to identify the reasonable and practicable countermeasures necessary to upgrade the controllability performance of the truck (or truck combination) to the level indicated. Previous research shows that some corrective steps apply to the design and construction of the vehicle constituting the powered unit, whereas other corrective steps apply to operational and maintenance practices.

References

1. Segel, L., et al.: Mechanics of Heavy-Duty Trucks and Truck Combinations, The University of Michigan Engineering Summer Conferences, 1985.

2. Segel, L. and Ervin, R.D. "The Influence of Tire Factors on the Stability of Trucks and Tractor Trailers." Vehicle System Dynamics, Vol. 10, 1981, pp. 39-59.

3. MacAdam, C.C. "A Computer-Based Study of the Yaw/Roll Stability of Heavy Trucks Characterized by High Centers of Gravity." SAE Paper #821260, 1982.

4. Winkler, C.B., Fancher, P.S., and MacAdam, C.C.: Parametric Analysis of Heavy Duty Truck Dynamic Stability, final report. UMTRI, May 1983. 2v. Report no., UMTRI-83-13. Sponsored by the National Highway Traffic Safety Administration. Contract no. DTNH-22-80-C-07344. (DOT/HS 806 411 and DOT/HS 806 412).

5. Fancher, P.S.: "An Evaluation of the Obstacle-Avoidance Capabilities of Articulated Commercial Vehicles." The University of Michigan Transportation Research Institute, 10th International Conference on Experimental Safety Vehicles, Oxford, England. July 1-5, 1985.

6. Fancher, Paul S.: "The Static Stability of Articulated Commercial Vehicles," Vehicle System Dynamics, 14(1985), pp. 201-227.

2.4 Oscillatory Behavior of Multi-Articulated Highway Trains

2.4.1 Mechanics. In addition to the aspects of vehicle design and operation which establish whether a truck will respond to steering in a stable (convergent) manner, combination vehicles, specifically an articulated vehicle, can exhibit oscillatory behavior. This behavior can be excited by a steering action or by any other kind of road or wind disturbance. Typically, it manifests itself as angular displacements of trailing units relative to the orientation of the preceding unit with these angular displacements occurring in a cyclic or an oscillatory manner. The actual number of oscillatory motions, each with its own natural frequency, depend on the number of mass units that are joined together by pivots or hinges, constituting an articulation joint. The individual oscillatory motions may be well damped or lightly damped and, under certain conditions, may be a divergent oscillation, namely, an oscillation which grows in time in an exponential manner [1].

Prior research has, in large measure, identified the design and operating conditions which lead to either lightly damped or unstable oscillations. In general, information is available on how (1) the geometry of the vehicle system (namely, the location of axles and articulation hinges with respect to the various mass centers), (2) the mechanics of tires and steering mechanisms, and (3) vehicle speed influence the damping or stability of the individual oscillatory motions. For example, studies have shown that design features which promote good tracking (i.e., trailing fidelity) at very low speed are likely to cause the oscillatory motions at finite speed to be more lightly damped [2]. Further, for each mass unit and articulation hinge added to the vehicle system, the more lightly damped the additional oscillatory mode of motion becomes, increasing the potential for a divergent oscillation as speed is further increased [1,3].

Clearly, the above noted behavior places an upper limit on the number of articulated mass units which can be incorporated into a so-called "highway train." At the present time, oscillatory trailer motions are seen as compromising the viability of certain types of multi-trailer combinations. Perhaps the most common cases in which oscillatory behavior occurs in vehicles in the U.S. involve situations in which the payload is improperly distributed in "doubles" or "triples" combinations. Although the oscillation may not be sufficiently large to threaten the driver's ability to control the trajectory of the powered unit, it may be of concern insofar as the trailing units may encroach on other travel lanes or intimidate other motorists and thereby cause anomalous maneuvering actions.

2.4.2 Significance and the Prospects for Improvement. Given that oscillatory phenomena are only likely to occur with the use of doubles or triples combinations (or perhaps with a truck-full trailer combination), limited experience exists in the U.S. to demonstrate that oscillatory phenomena, per se, make a significant contribution to the accident record. On the other hand, there is ample evidence that the response of trailing units to rapid steering maneuvers can result in the rearmost unit experiencing an acceleration sufficient to roll this unit over. The primary need is for officials and legislators to realize that road-use laws governing the size, weight, and configuration of articulated vehicles can promote the use of vehicles which will exhibit a highly oscillatory behavior. Although there is an understanding within the research community as to how the desire to increase the productivity of trucking (by the adoption of new laws) can conflict with the requirement to obtain vehicles that behave in a well-damped manner, there is a need to reduce this understanding to sets of guidelines which can be easily understood and applied by all of the parties involved. Whereas some of these guidelines are needed for lawmakers (or regulators) and vehicle designers, there are also guidelines that are needed by those who control or monitor the manner in which vehicles are loaded and unloaded. With the conduct of further research, it is conceivable that designs can be identified which will demonstrate improved tradeoffs between trailing fidelity, dynamic stability, and productivity gains.

References

1. Mallikarjunarao, C. and Fancher, P. "Analysis of the Directional Response Characteristics of Double Tankers." SAE Paper No. 781064, 1978.

2. Fancher, P.S. and Segel, L. "Offtracking Versus Stability and Dynamic Response of the Trackless Train." Proceedings, 8th IAVSD Symposium, Cambridge, Mass., August 1983.

3. Ervin, R.D. and Mallikarjunarao, C. "A Study of the Yaw Stability of Tractor-Semi-Trailer Combinations." 7th IAVSD Symposium, Cambridge, England, September 1981.

3.0 RESEARCH PROGRAM

3.1 Logical Organization and Justification of the Research Program

In order to acquire an information base for guiding decisions on safety regulations, the research plan addresses the following topics:

Definitions of safety-related response phenomena

Demonstrations of links to truck accidents

An inventory of the performance of the truck fleet

Determination of feasible countermeasures

Development of regulatory procedures

Projections of costs and benefits

These topics form the elements of the information base.

The generic interrelationships between these elements are illustrated in Figure 3.1.1. The "hub" of this approach (represented by the circle in Figure 3.1.1) is the previous work that has been done in developing engineering definitions of safety-related response phenomena of heavy trucks. From this engineering foundation, defining pertinent aspects of vehicle performance, the research program expands into the topics that need to be investigated in order to develop the information required to perform cost-benefit studies (see the rectangular blocks in Figure 3.1.1). The outcome of the cost-benefit work is a set of performance requirements and associated levels of performance that are justifiable given the results of the investigations of the other topics.

In this conceptual framework, the persons selecting levels of performance will weigh the tradeoffs between costs and benefits in determining the boundaries between acceptable and unacceptable performance. They (the regulators) will be expected to set levels of performance that will provide a reasonable balance between costs and benefits.

In addition to the operational benefits of promoting vehicles with improved response to steering control, the performance standards are to be based on vehicle characteristics that have an impact on safety. One of the primary elements of the research will be to demonstrate the links between vehicle properties and truck accidents. Based

INFORMATION BASE FOR GUIDING DECISIONS ON SAFETY REGULATIONS

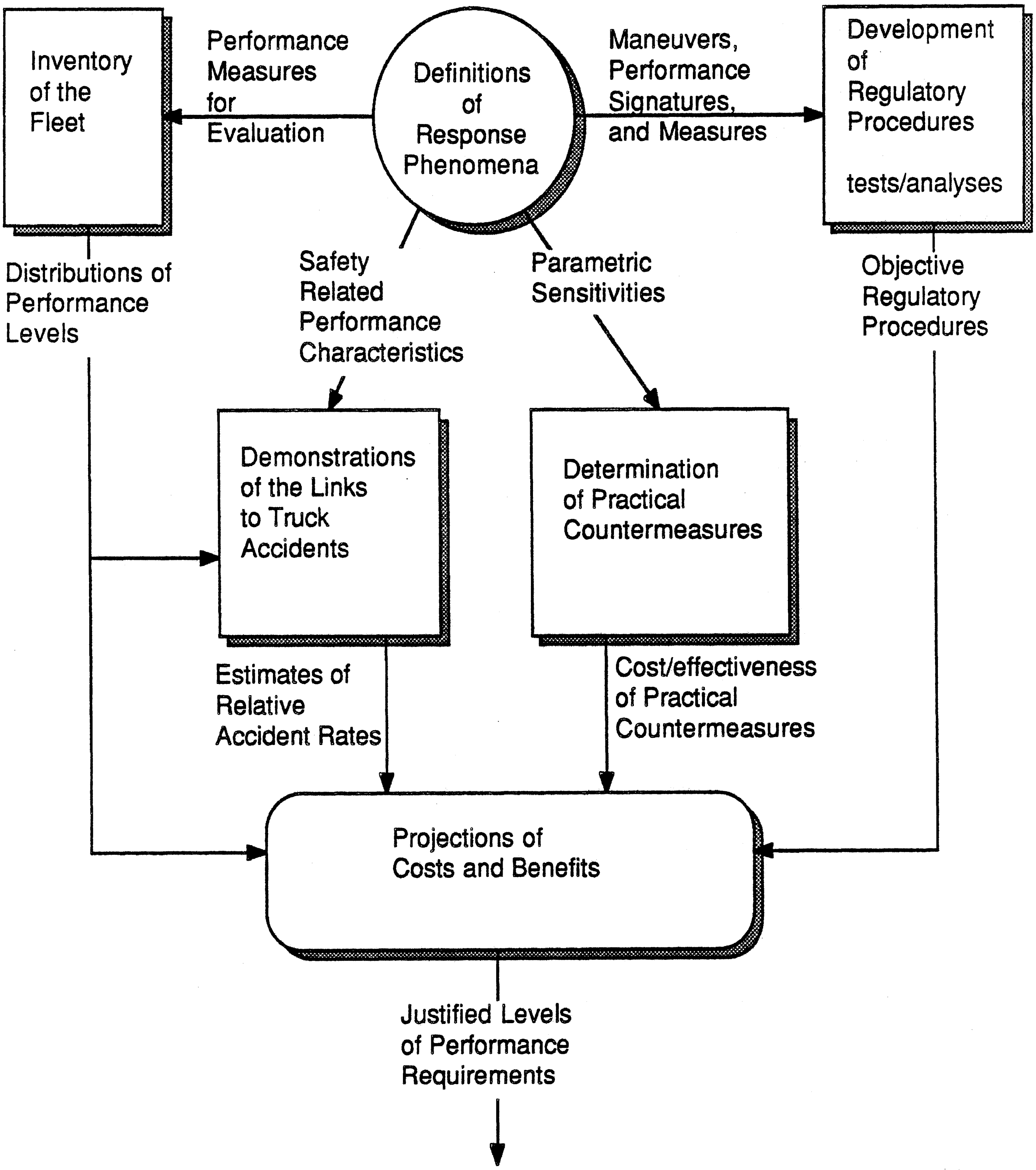


Figure 3.1.1 Information base for guiding decisions on safety regulations

upon the synthesis of knowledge and past experience in heavy truck mechanics, the following aspects of steering control have been singled out for examination:

Rollover immunity

Trailing fidelity, comprised of
  rearward amplification and high- and low-speed offtracking

Controllability under slippery conditions

Steering controllability of the power unit

Damping of oscillatory yaw motions

In total, there are seven aspects of maneuvering performance, including the three aspects of trailing fidelity, that are to be pursued in this research program.

The scope of the research program is described and defined by a five-by-seven matrix of cells covering (a) the five topics pertaining to the elements of the information base and (b) the seven vehicle performance areas pertaining to steering control (see Table 3.1.1). Clearly, the work in each column is intended to lead to a safety regulation. Hence, the plan for the research program is organized to correspond to a column by column examination of Table 3.1.1.

The numbers across the top of Table 3.1.1 indicate the priorities that have been assigned to various vehicle response areas. These priorities reflect both (a) the adequacy of the knowledge currently available for developing a workable safety standard and (b) the potential for obtaining quantifiable safety benefits.

"Rollover Immunity" is given the highest (number one) priority because researchers have a good understanding of the basic phenomena involved and they have already demonstrated links to safety in this area. In addition, rollover is easy to identify and observe. It is a vehicle response property that is, in itself, an accident. (Jackknifing is the only other steering response phenomenon that is an accident even if nothing else happens.)

The next three columns (2 through 4) may be combined someday into a single trailing-fidelity standard because vehicle properties influence rearward amplification and high- and low-speed offtracking in opposite ways. That is, vehicle changes that improve low-speed offtracking may degrade high-speed offtracking and rearward amplification. Low-speed offtracking has received much attention because vehicles with long wheelbases have such large amounts of offtracking that they cannot operate within normally available spaces. Although low-speed offtracking leads to property damage accidents and traffic

Table 3.1.1 Matrix describing the research program (continued on the next page)

		1	2	3	4	5
	Vehicle Areas Base Elements	Rollover Immunity	Rearward Amplification	High-speed Offtracking	Low-speed Offtracking	Controllability under Slippery Conditions
			←Trailing	Fidelity	→	
A	Definitions of Response Phenomena	-roll dynamics -driver/ vehicle	-roll dynamics -driver/ vehicle	-transient turning	-transient turning	-tire cornering traction problems
B	Inventory of the Fleet	-distribution of rollover thresholds	-distribution of rear. amp.	-dist. of offtracking	-dist. of offtracking	-inventory of tire status and vehicle loading
C	Demon- strations of the Links to Truck Accidents	-demand survey Ay -accident analysis	-demand survey Ay and freq. -accident analysis	-demand survey Ay -accident analysis -ramp driving study	-survey of turning conflicts -accident analysis	-demand survey Ay -wet loss of control
D	Deter- mination of Practical Counter- measures	-"cost/ effectiveness" estimates	-"cost/ effectiveness" estimates	-"cost/ effectiveness" estimates	-"cost/ effectiveness" estimates	-"cost/ effectiveness" estimates
E	Devel- ment of Regulatory Procedures	-test procedure	-test procedure	-test procedure	-test procedure	-test procedure

Table 3.1.1 Matrix describing the research program (continued)

	Vehicle Areas / Base Elements	6 Steering Controllability of the Power Unit	7 Damping of Oscillatory Yaw Motions
A	Definitions of Response Phenomena	-phase 1 driver modeling, phase 2 driver/ vehicle study	-study of oscillatory mechanics
B	Inventory of the Fleet	-depends upon 6A to set a performance measure	-inventory of loading, layout, etc.
C	Demonstrations of the Links to Truck Accidents	-depends upon 6A to define a maneuver -accident analysis	-survey depends on 7A -accident analysis
D	Determination of Practical Countermeasures	-"cost/ effectiveness" estimates	-"cost/ effectiveness" estimates
E	Devel-ment of Regulatory Procedures	-test procedures for tractors and trucks	-test procedure for trailers -guidelines for locating and loading the hitch on a towing unit

intrusions and delays, it may not be an important contributor to more serious accidents. On the other hand, rearward amplification is known to contribute to the rollover of multi-articulated vehicles, and high-speed offtracking has lead to curb and shoulder tripping. Of these two response issues, rearward amplification is given the higher priority.

"Controllability under slippery conditions" is assigned next priority. This pertains primarily to the ability of the vehicle's tires to provide enough side force for steering maneuvers when the road is wet or slippery. The efforts directed at this phenomenon may lead to a different type of standard. Possibly, they will lead to a tire regulation along with some type of vehicle performance requirement.

Although considerable engineering expertise exists in the area of the steering controllability of the power unit, the development of a safety standard in this area will require an improved understanding of the driver as the control element in the driver/vehicle system. Given that many accidents occur on curves, there may be a chance for a big payoff if steering controllability can be improved. However, this is the area that appears to require the most technical development before the information base can be expanded as required for developing safety regulations.

With regard to the units of combination vehicles, engineering analyses indicate that steering controllability is mainly influenced by the properties of the tractor. The driver steers the tractor and the other units in the combination are expected to follow. Hence, vehicle performance in trailing fidelity can be separated from performance in steering controllability. Steering controllability would probably be regulated by a tractor test using a reference trailer for loading the tractor.

Damping of oscillatory yaw motions is the last performance phenomenon considered in the plan. Oscillatory phenomena are usually eliminated or controlled in the evolution of a combination vehicle type because they are evident and they scare people. However, new designs are often tried with poor hitching and loading arrangements. There are no simple guidelines available for designing combination vehicles that will have appropriate amounts of damping of yaw oscillations. The purpose of this activity is to provide guidance that will aid in ensuring the development of stable combination vehicles.

The rows of Table 3.1.1 correspond to the elements of the information base as discussed in connection with Figure 3.1.1. For example, row "A" represents the engineering definitions of the response phenomena including descriptions of pertinent driving maneuvers, test or analytical results that can be used to characterize performance, measures that can be used to compare performance, and the sensitivity of performance to changes in vehicle properties. In general, the inventory of the fleet (row B) contributes to (a) a "probability" analysis of accident likelihood, and (b) the final assessment of how many vehicles would need to be modified through practical countermeasures. By examining the entries in the first two rows of the matrix (Table 3.1.1), one can see that there is a noticeable amount of repetition in these cells. These repetitions indicate possibilities for obtaining efficiencies by combining efforts between the activities associated with the various vehicle performance areas. Clearly, the efforts required to build the information base have similarities across any given row.

The entries in row C of Table 3.1.1, corresponding to the links to accidents, contain "demand surveys" and "accident analyses." The demand surveys contribute to the probability analyses mentioned earlier in connection with the fleet inventory. The symbol "Ay" in row C of Table 3.1.1 stands for the lateral acceleration acting on the vehicle, that is, the side force required to cause a vehicle of given weight to respond to steering as desired. A number of the cells of the matrix contain Ay, indicating multiple uses for a survey of this valuable information.

The accident analyses are of a special type designed to demonstrate the influence of vehicle properties on truck accidents. There are methodological problems to be resolved, but the anticipated approach is a generalization of the one applied to rollover accidents as discussed in connection with Figure 2.1.3. The intention is to select accident types that are appropriate to the vehicle characteristic at issue. It will be neccessary to be able to estimate the values of the performance measures associated with the vehicles involved in the pertinent types of accidents. Then, one can construct graphs that show the relative frequencies of accidents versus the levels of vehicle performance qualities. These graphs are needed to compare the safety benefits that could be obtained by setting various bounds on vehicle performance. They are needed for the benefit part of the benefit/cost comparisons.

A theoretical understanding of the improvements in vehicle performance to be made by changing vehicle properties is available from the engineering study (row A). However, some of these "fixes" may limit productivity, increase vehicle production costs, make driving unpleasant, or cause safety problems greater than the one being fixed. Fleet owners, manufactures, maintenance personnel, drivers, and researchers need to contribute to the base of information on what is practical and how much it will cost. Ingenious technical solutions will be considered in the efforts on countermeasures.

The regulatory procedures themselves are a key part of the information base. The pass/fail levels of the performance measures will be set by choosing levels that provide acceptable relationships of benefits to costs. Work is to be done in this area to obtain objective and repeatable test and/or analytical procedures suitable for the regulatory process in a form that can be performed simply without undue complications or hardship.

Some of the cells of the matrix contain more than one entry indicating that two or three projects will contribute to the information pertaining to that cell. The following section details the projects and the timing and costs involved with the research plan.

3.2 A Time-Scaled Plan of Research on the Stability and Control of Trucks

In this section, a plan of research is recommended for establishing the safety-related performance properties of trucks and for developing the knowledge needed to regulate such characteristics. The plan constitutes a set of research studies which are organized according to the seven vehicle performance areas and the five elements of the information base discussed earlier in Table 3.1.1. Following the order presented in Table 3.1.1, the research plan will be illustrated in seven individual schedules, beginning with the highest "priority" vehicle performance area. (Note that the "priority" reflects the extent to which the performance area is both well-defined, at present, and has a demonstrable safety connection.)

Shown in Figure 3.2.1, for example, is the schedule of research studies addressing the rollover performance area. The open blocks on the chart indicate studies which:

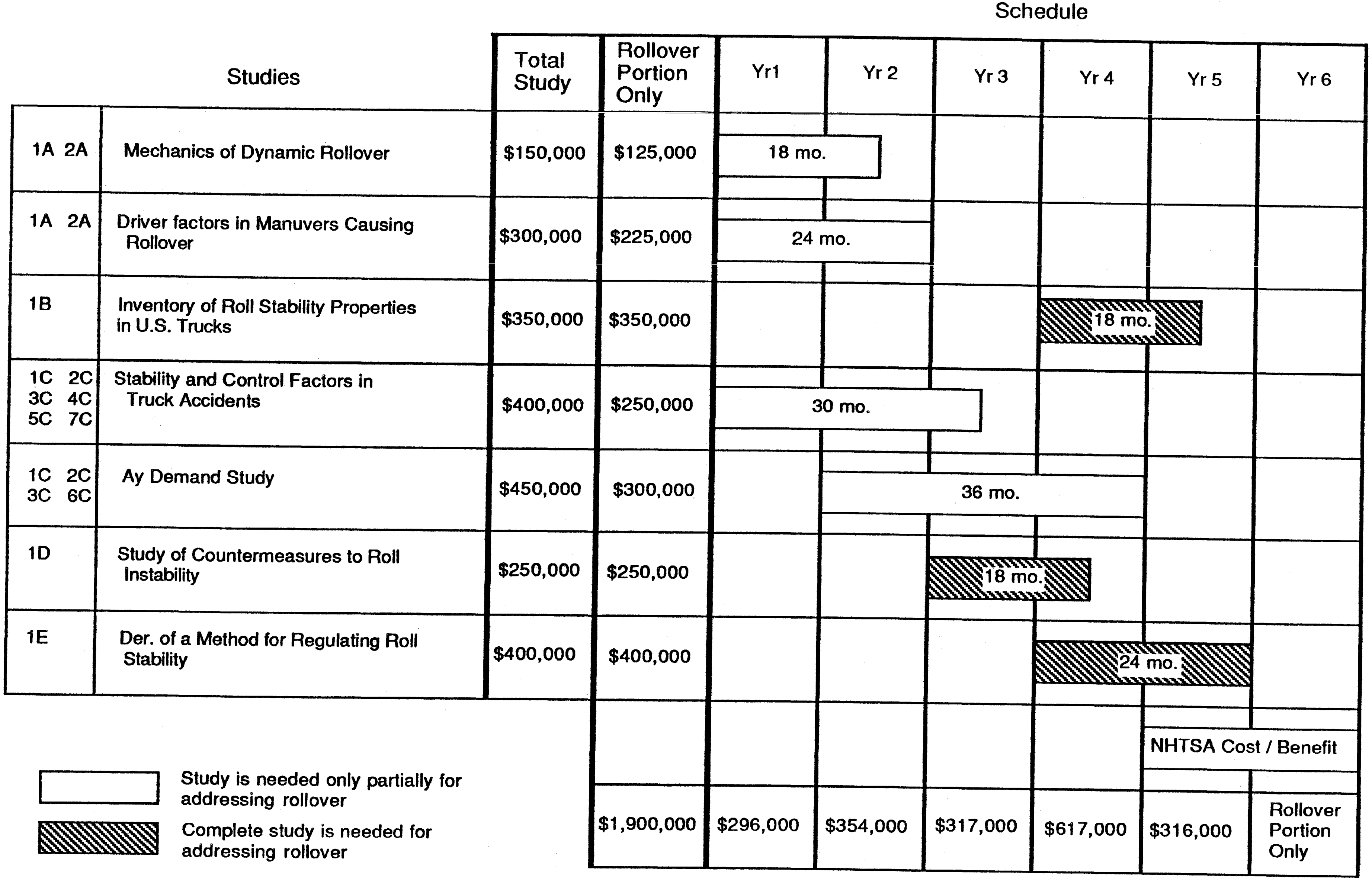
a) involve a methodology which is common to other vehicle performance areas,

b) entail a substantial front-end investment in setting up the research technique

c) should be linked, for efficiency sake, with the corresponding efforts needed in the other performance areas.

All such studies which have common methodologies have been incorporated in the plan as if the entire combined effort would be undertaken. The respective performance areas which become addressed in each such common study are listed by the number of the performance area (see Table 3.1.1) to the left of the project title. These so-called "common" projects have been roughly costed so as to apportion the overall project budget into the respective parts attributable to each performance area. In each case, the highest "priority" performance area always absorbs the "front-end" portion of the project cost. As a case in point, consider the second project in the rollover area, Figure 3.2.1, entitled

① Rollover



	Studies	Total Study	Rollover Portion Only	Schedule Yr1	Yr 2	Yr 3	Yr 4	Yr 5	Yr 6
1A 2A	Mechanics of Dynamic Rollover	$150,000	$125,000	18 mo.					
1A 2A	Driver factors in Manuvers Causing Rollover	$300,000	$225,000	24 mo.					
1B	Inventory of Roll Stability Properties in U.S. Trucks	$350,000	$350,000				▨ 18 mo.		
1C 2C 3C 4C 5C 7C	Stability and Control Factors in Truck Accidents	$400,000	$250,000	30 mo.					
1C 2C 3C 6C	Ay Demand Study	$450,000	$300,000		36 mo.				
1D	Study of Countermeasures to Roll Instability	$250,000	$250,000			▨ 18 mo.			
1E	Der. of a Method for Regulating Roll Stability	$400,000	$400,000				▨ 24 mo.		
								NHTSA Cost / Benefit	
			$1,900,000	$296,000	$354,000	$317,000	$617,000	$316,000	Rollover Portion Only

RESEARCH EXPENDITURES PER YEAR

☐ Study is needed only partially for addressing rollover

▨ Complete study is needed for addressing rollover

Figure 3.2.1 Rollover Activities

"Driver Factors in Maneuvers Causing Rollovers." This project requires a substantial front-end investment for developing an experimental method which is then used in behalf of both the rollover and rearward amplification performance areas. The columns listing project costs show that $225,000 out of the total $300,000 would be needed to accomplish the objectives of the rollover area, by itself. It follows that an additional $75,000 covers the further application of the method to address the rearward amplification subject.

The studies which are shown as cross-hatched blocks are those in which the complete effort is exclusively devoted to addressing the immediate performance area -- in this case, rollover. The plan shows one or more of either the "exclusive" or "common"-type projects for meeting the needs of each of the five elements of the knowledge base. Each study is placed on the time schedule so that the need for knowledge flow from one project to the next is satisfied.

As indicated above, each project is shown with an estimated total cost as well as a portion of the total allocable to the performance area at hand. The sum of all of the apportioned costs which are directly attributable to the projects in, say, the rollover subject area, are entered to show the total expenditure needed in that area. Similarly, the expenses in the rollover area, by year, represent the total of the apportioned costs within each year, assuming a linear rate of funds commitment to each project over its term.

In the subsections which follow, the research recommended for each performance area will be briefly discussed. A more detailed presentation of the objectives and methods of the individual research projects is presented in Appendix A.

Rollover

Referring, again, to Figure 3.2.1, the plan of rollover-related research entails a total of seven projects which provide the knowledge base for a NHTSA cost/benefit determination relative to rulemaking. The studies are as follows:

- an engineering study of various dynamic considerations pertinent to defining good overall roll stability performance. This work would assure that rulemaking based upon the static roll stability work done to date would not err in overlooking some important dynamic factor.

- a study of the driver sensations associated with avoiding rollover. Experiments in which real truck drivers would operate differing trucks near the rollover limit (with protective devices) would indicate other aspects of vehicle design which might aggravate or benefit the driver's ability to sense the proximity to rollover.

- a sampled inventory of the U.S. trucking fleet so as to estimate the distribution of roll stability properties across the fleet. Special measurements would be made on trucks at the roadside and analysis would project the results to the national fleet level.

- an accident data study would refine prior analyses linking static roll stability with rollover accidents. Accident links for all popular truck configurations would be examined. An in-depth follow-up method is used to supplement mass accident data with additional information which better describes vehicles which have rolled over.

- a field experiment is developed in which real trucks are instrumented with a data-logging system to monitor the way trucks are driven. The experiment is conducted on differing trucks with differing drivers in operations across the U.S. to establish the "demands" which are made on vehicle roll stability from day to day. A probability analysis of the results will project the relationship between stability level and the likelihood of rollover, given the demands which exist. This project parallels the accident data study and provides a supplemental path for linking stability level with safety.

- a set of candidate approaches toward improving truck roll stability will be examined for technical feasibility and practicality of implementation. The study provides example means of vehicle improvement which warrant consideration in the cost/benefit study.

- a method for defining, measuring, and specifying roll stability performance is developed. The method provides the specification context in which to stipulate a safety standard.

The set of rollover studies requires a period of five years to complete and costs a projected total of $1,900,000, although a large portion of that total goes to front-end costs which benefit the study of other performance areas.

Rearward Amplification

Shown in Figure 3.2.2 is a plan for research on the rearward amplification phenomenon which leads to premature rollover of the rear trailers in multi-trailer combinations. The individual studies are briefly described as follows:

- an extension of the engineering study of "rollover dynamics" which was undertaken in behalf of basic rollover concerns, is devoted to the dynamic aspect of rollover of rear trailers due to rearward amplification. This portion of the study delineates the peculiarly "dynamic" properties which tend to influence the overall potential for a rollover under such conditions.

- an extension of the driver/vehicle experiments also conducted in behalf of basic rollover concerns addresses the steering behavior of truck drivers insofar as inputs can be applied to excite rearward amplification. In part, this work aids in demonstrating to the trucking community the extent to which the critical steering may be applied by real drivers on the road.

- a sampled inventory of the fleet of multi-trailer-type vehicles is conducted to ascertain the prevalence of certain key properties influencing rearward amplification. The rearward amplification subject provides the front-end setup of the sampling scheme and the in-field data collection methodology which is then employed in behalf of four additional performance areas (No's 3,4,5, and 7).

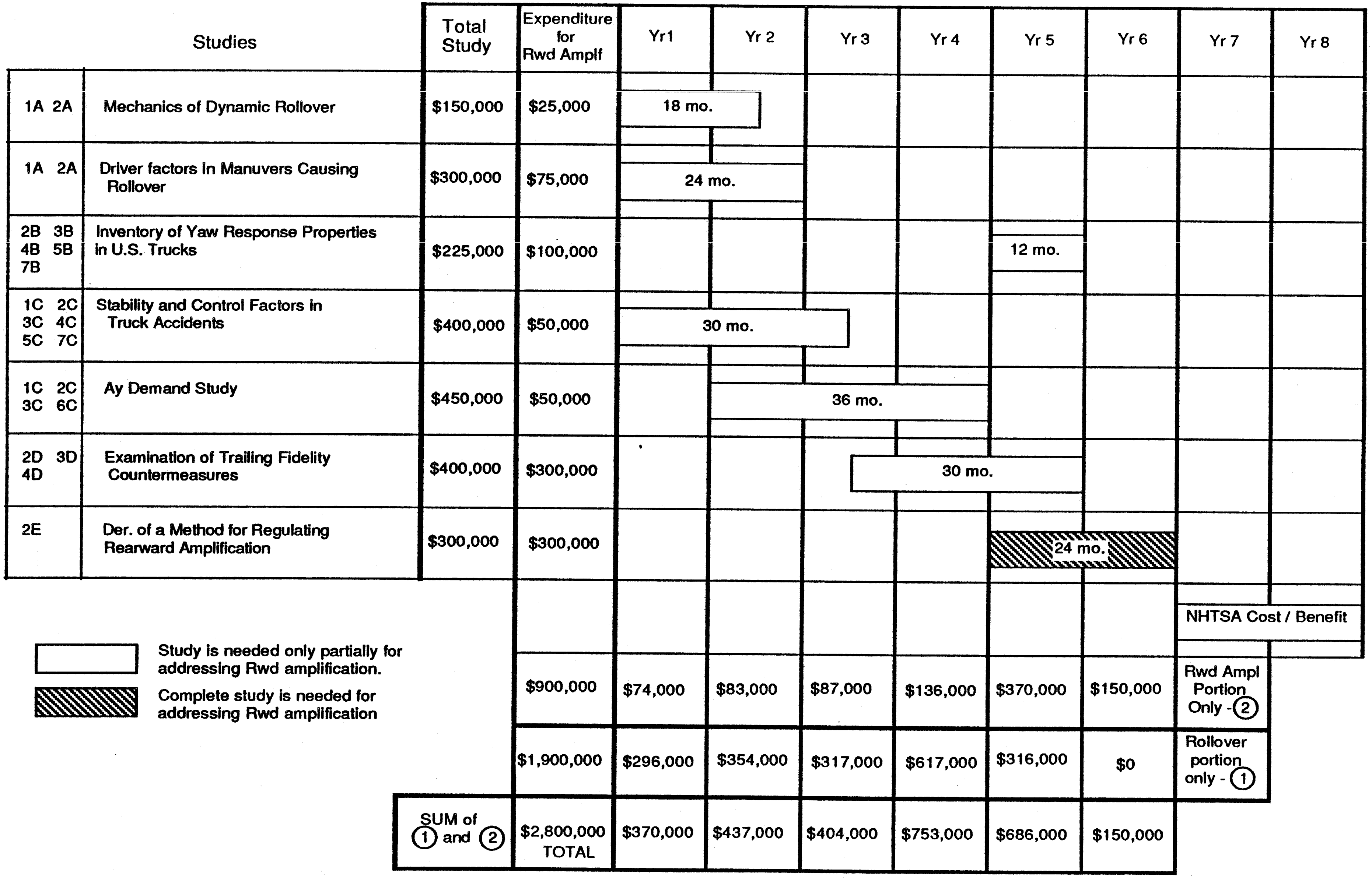
- the accident data study initiated in behalf of basic rollover interests is expanded to cover the examination of accidents in which the rear trailers of doubles, triples, and truck/full-trailers have rolled over. The intent, again, is to directly define the linkage between rearward amplification properties and involvement in this peculiar accident type.

- the field experiment which collects data on the maneuvering actions of instrumented trucks in actual service is extended to permit prediction of the amplitude and frequency content of lateral motions in doubles, triples, and truck/full-trailers. An analysis method is developed and applied to laying out the probability that the motion demands will exceed the tolerances of truck combinations having differing levels of rearward amplification.

- the candidate approaches toward reducing rearward amplification behavior while preserving the qualities needed in productive trucking are examined. Technical

② Rearward Amplification

Schedule



	Studies	Total Study	Expenditure for Rwd Amplf	Yr1	Yr 2	Yr 3	Yr 4	Yr 5	Yr 6	Yr 7	Yr 8
1A 2A	Mechanics of Dynamic Rollover	$150,000	$25,000	18 mo.							
1A 2A	Driver factors In Manuvers Causing Rollover	$300,000	$75,000	24 mo.							
2B 3B 4B 5B 7B	Inventory of Yaw Response Properties in U.S. Trucks	$225,000	$100,000					12 mo.			
1C 2C 3C 4C 5C 7C	Stability and Control Factors in Truck Accidents	$400,000	$50,000	30 mo.							
1C 2C 3C 6C	Ay Demand Study	$450,000	$50,000		36 mo.						
2D 3D 4D	Examination of Trailing Fidelity Countermeasures	$400,000	$300,000			30 mo.					
2E	Der. of a Method for Regulating Rearward Amplification	$300,000	$300,000					▨ 24 mo. ▨			
										NHTSA Cost / Benefit	
			$900,000	$74,000	$83,000	$87,000	$136,000	$370,000	$150,000	Rwd Ampl Portion Only -②	
			$1,900,000	$296,000	$354,000	$317,000	$617,000	$316,000	$0	Rollover portion only - ①	
		SUM of ① and ②	$2,800,000 TOTAL	$370,000	$437,000	$404,000	$753,000	$686,000	$150,000		

☐	Study is needed only partially for addressing Rwd amplification.
▨	Complete study is needed for addressing Rwd amplification

RESEARCH EXPENDITURES PER YEAR

Figure 3.2.2 Rearward Amplification Activities effectiveness and practical considerations are weighed in recommending those approaches which warrant inclusion in the study of cost and benefits of a regulation.

- a method for defining, measuring, and specifying rearward amplification performance is developed, as the basis for formulating a regulation document.

A total of seven projects are seen as needed for addressing the rearward amplification area. The portion of the project costs which are directly attributed to the rearward amplification subject is $875,000, although many of the listed projects were premised on the front-end investment covered under the rollover research program. The respective yearly commitments needed on this subject are listed at the bottom of the time schedule. The total and yearly costs of the roll stability research program from Figure 3.2.1 are then added to the apportioned costs for rearward amplification to provide the "running total" at the bottom of the sheet.

High-Speed Offtracking

Shown in Figure 3.2.3 is the plan of research on the subject of high-speed offtracking. This set of projects constitutes one of the smaller undertakings in the overall program, reflecting the relative simplicity of the high-speed offtracking problem as well as the efficiencies accrued from the front-loading of studies onto the higher priority performance areas. The projects in high-speed offtracking are as follows:

- an engineering study of certain issues involving the mechanics of offtracking. The transient aspect of high-speed offtracking is of special interest since there are indications that overshoots in outboard offtracking can occur during transient turning, say, upon entering an exit ramp. The study will also examine the influence of spread axles and other system parameters (with particular attention to suspension kinematics) on both the transient and steady-state aspects of high-speed offtracking.

- a sampled inventory of those aspects of truck configuration influencing high-speed offtracking will be obtained. This inventory data will enable a projection of the distribution of such characteristics in the national truck population.

- the accident data study mentioned earlier will contain elements for examining the kinds of accidents which may result from high-speed offtracking. The focus will be, of course, on accidents at curving roadways and ramps on which outboard

③ High - Speed Offtracking

	Studies	Total Study	Expenditure for Hi-Spd Offtracking	Yr1	Yr 2	Yr 3	Yr 4	Yr 5	Yr 6	
				Schedule						
3A 4A	Study of Specific Issues in the Mechanics of Offtracking	$150,000	$125,000		12 mo.					
2B 3B 4B 5B 7B	Inventory of Yaw Response Properties in U.S. Trucks	$225,000	$25,000					12 mo.		
1C 2C 3C 4C 5C 7C	Stability and Control Factors in Truck Accidents	$400,000	$25,000	30 mo.						
3C	Study of Hi-Spd Offtracking in Actual Service	$200,000	$200,000		▨ 18 mo.					
1C 2C 3C 6C	Ay Demand Study	$450,000	$50,000		36 mo.					
2D 3D 4D	Examination of Trailing Fidelity Countermeasures	$400,000	$50,000			30 mo.				
3E	Development of Method for Regulating High Speed Offtracking	$200,000	$200,000					▨ 12 mo.		
								NHTSA Cost / Benefit		
			$675,000	$10,000	$156,000	$228,000	$36,000	$145,000	$100,000	Hi-Speed Offtracking Only - ③
			$2,800,000	$370,000	$437,000	$404,000	$753,000	$686,000	$150,000	SUM of ① and ②
	SUM of ①, ② and ③		$3,475,000	$380,000	$593,000	$632,000	$789,000	$831,000	$250,000	

□ Study is needed only partially for addressing Hi-Speed Offtracking

▨ Complete study is needed for addressing Hi-Speed Offtracking

RESEARCH EXPENDITURES PER YEAR

Figure 3.2.3 High-Speed Offtracking Activities trailer motions might result in curb-tripping and a peculiar class of collisions involving the trailer.

- a study of the axle paths and vehicle speeds actually occurring on curved roadways and ramps in order to establish how trucks are actually driven. The measurements will be used together with the acceleration demand information in the large data-logging study, below, to enable the conduct of a probability analysis for predicting accident rates due to high-speed offtracking.

- the in-field data-logging study discussed earlier will include analysis algorithms which are designed to predict the high-speed offtracking motions which the trailers of differing vehicle configurations would exhibit, given the time histories of lateral motions initiated at the tractor.

- approaches toward improving high-speed offtracking performance will be examined to identify candidates which are suitable from an engineering point of view, thus warranting inclusion in a cost/benefit study.

- a measurement method for supporting a high-speed offtracking performance requirement would be developed.

The total set of seven projects relating to high-speed offtracking cover a period of 5-1/2 years, with a total cost of $675,000.

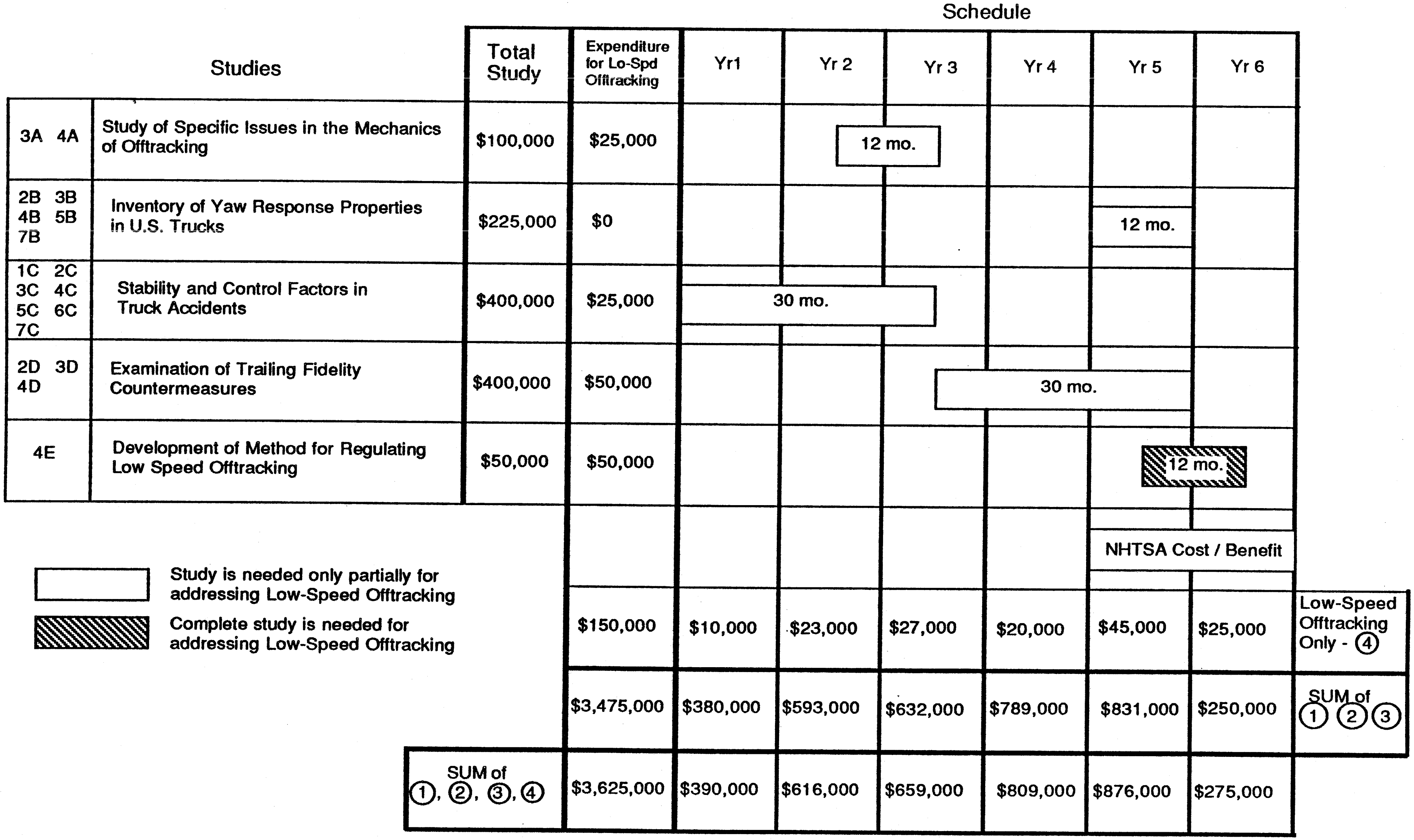
Low-Speed Offtracking

The research recommended for low-speed offtracking, shown comprising five projects in Figure 3.2.4, is the smallest-scale effort in the program. The safety problems posed by low-speed offtracking will be examined in the other, front-loaded, projects, while only a study of regulatory methodology is seen as required exclusively for examining this performance area. The projects addressing low-speed offtracking are as follows:

- a study of certain mechanical aspects of low-speed offtracking not examined in prior research. The study would address problems posed by spread axle tandems while turning on tight-radius paths, especially under low-friction conditions.

- the sampled inventory of truck configurations needed for high-speed offtracking, above, provides the same data as are needed to evaluate the low-speed offtracking properties. Thus, no new data are gathered specifically in behalf of low-speed

④ Low - Speed Offtracking



Schedule

	Studies	Total Study	Expenditure for Lo-Spd Offtracking	Yr1	Yr 2	Yr 3	Yr 4	Yr 5	Yr 6	
3A 4A	Study of Specific Issues in the Mechanics of Offtracking	$100,000	$25,000		12 mo.					
2B 3B 4B 5B 7B	Inventory of Yaw Response Properties in U.S. Trucks	$225,000	$0					12 mo.		
1C 2C 3C 4C 5C 6C 7C	Stability and Control Factors in Truck Accidents	$400,000	$25,000	30 mo.						
2D 3D 4D	Examination of Trailing Fidelity Countermeasures	$400,000	$50,000				30 mo.			
4E	Development of Method for Regulating Low Speed Offtracking	$50,000	$50,000					▨ 12 mo.		
								NHTSA Cost / Benefit		
			$150,000	$10,000	$23,000	$27,000	$20,000	$45,000	$25,000	Low-Speed Offtracking Only - ④
			$3,475,000	$380,000	$593,000	$632,000	$789,000	$831,000	$250,000	SUM of ① ② ③
		SUM of ①, ②, ③, ④	$3,625,000	$390,000	$616,000	$659,000	$809,000	$876,000	$275,000	

☐	Study is needed only partially for addressing Low-Speed Offtracking
▨	Complete study is needed for addressing Low-Speed Offtracking

RESEARCH EXPENDITURES PER YEAR

Figure 3.2.4 Low-Speed Offtracking Activities offtracking, but a U.S. fleet projection of this performance property will be obtained.

- the large accident study will include examination of truck collisions with other vehicles and fixed objects at intersections. Current research underway at FHWA will supplement these data with observations of traffic conflicts involving large truck combinations at intersections having restrictive geometry.
- countermeasures to low-speed offtracking will be studied not simply from the viewpoint of geometric wheelbases, but also considering steerable trailer axle arrangements such as currently found in other parts of the world. The study will identify those approaches toward minimizing low-speed offtracking which are found to be effective and practicable.
- an approach toward regulating low speed offtracking will be developed.

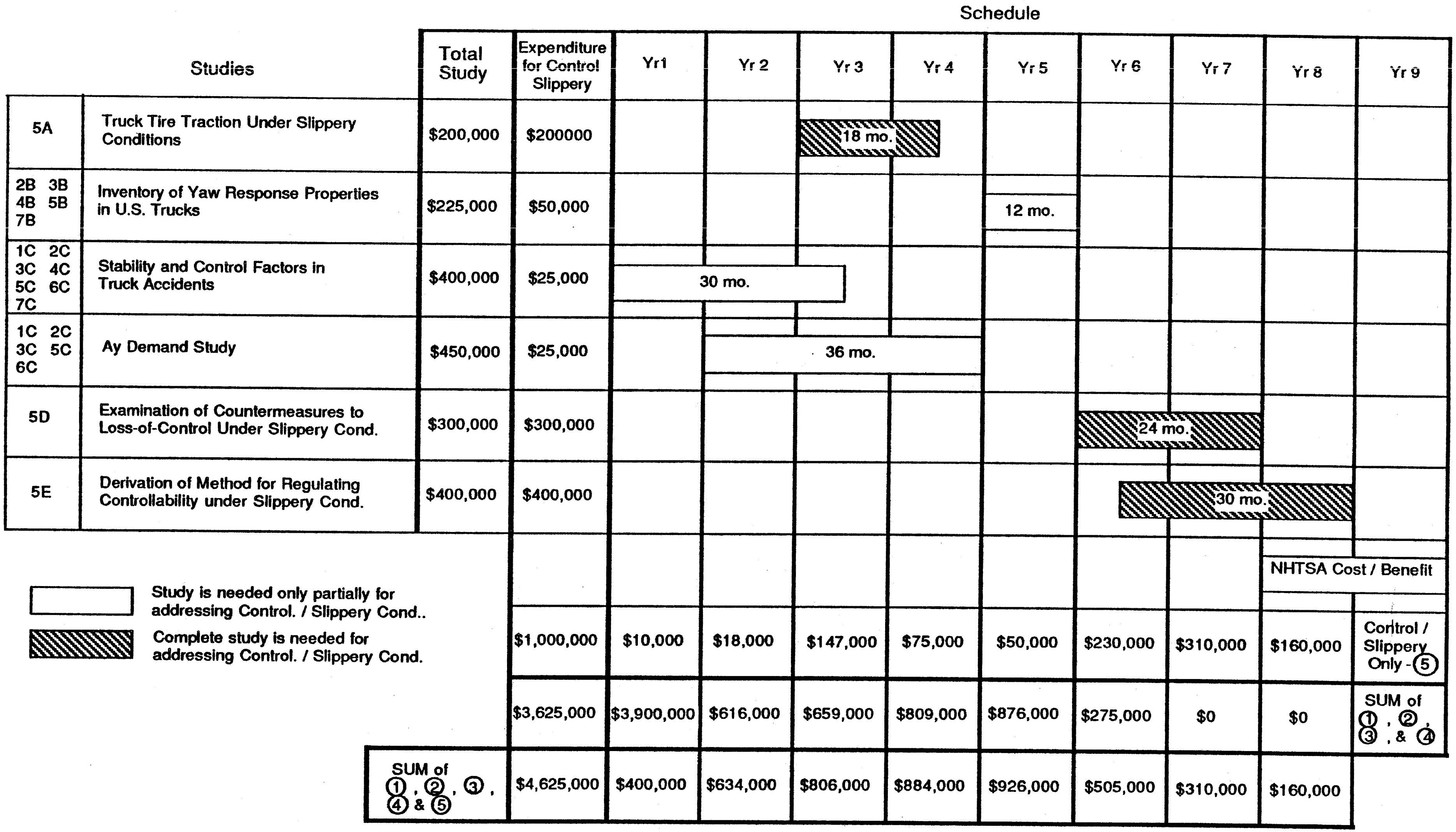
The program of effort on low-speed offtracking is estimated to cost $150,000 and covers a time period of 5.5 years.

Controllability Under Slippery Conditions

Shown in Figure 3.2.5 are the projects which contribute toward the knowledge base on the subject of controllability under slippery conditions. In general, these projects focus upon the tire/road interaction and are given importance in this overall program of research because the truck tire is known to be quite deficient in traction potential, especially on wet surfaces. The projects which follow from this observation are as follows:

- a study examining the mechanics of truck tire traction on wet pavement in order to clarify the operating conditions and tire design features which lead to an acute loss of frictional coupling. The study would include tire traction measurements on wetted pavements and an analysis of the truck maneuvering conditions in which control loss would be threatened by low traction performance.
- an addition to the sampled truck inventory project to include field information on tires in use and their states of tread depth. The results, together with the data on acceleration demand from the data-logging study, would permit estimation of the incidence of truck loss-of-control due to low tire traction level.

⑤ Controllability under Slippery Conditions



	Studies	Total Study	Expenditure for Control Slippery	Yr1	Yr 2	Yr 3	Yr 4	Yr 5	Yr 6	Yr 7	Yr 8	Yr 9
5A	Truck Tire Traction Under Slippery Conditions	$200,000	$200000			▨ 18 mo.						
2B 3B 4B 5B 7B	Inventory of Yaw Response Properties in U.S. Trucks	$225,000	$50,000					☐ 12 mo.				
1C 2C 3C 4C 5C 6C 7C	Stability and Control Factors in Truck Accidents	$400,000	$25,000	☐ 30 mo.								
1C 2C 3C 5C 6C	Ay Demand Study	$450,000	$25,000		☐ 36 mo.							
5D	Examination of Countermeasures to Loss-of-Control Under Slippery Cond.	$300,000	$300,000						▨ 24 mo.			
5E	Derivation of Method for Regulating Controllability under Slippery Cond.	$400,000	$400,000						▨ 30 mo.			
											NHTSA Cost / Benefit	
			$1,000,000	$10,000	$18,000	$147,000	$75,000	$50,000	$230,000	$310,000	$160,000	Control / Slippery Only - ⑤
			$3,625,000	$3,900,000	$616,000	$659,000	$809,000	$876,000	$275,000	$0	$0	SUM of ①, ②, ③, & ④
		SUM of ①, ②, ③, ④ & ⑤	$4,625,000	$400,000	$634,000	$806,000	$884,000	$926,000	$505,000	$310,000	$160,000	

☐ Study is needed only partially for addressing Control. / Slippery Cond..

▨ Complete study is needed for addressing Control. / Slippery Cond.

RESEARCH EXPENDITURES PER YEAR

Figure 3.2.5 Activities on Controllability under Slippery Conditions

- the accident data study would address truck loss-of-control accidents under slippery conditions. The results would supplement the accident predictions, above, based upon the analysis of acceleration demand data.

- the data-logging measurements in real trucks will yield data which is then analyzed, as mentioned above, for estimating truck loss-of-control events due to low tire traction level. The slippery/controllability subject area simply incurs additional costs for conducting the analysis portion of the effort.

- a substantial countermeasure assessment project is envisioned in which performance research would parallel the development of new tire design features. Also, the feasibility of constraining treadwear and tire loading extremes as alternative ways of reducing the problem would be studied.

- a method for regulating the traction level of truck tires on low-friction pavements would be developed and a model performance standard would be specified.

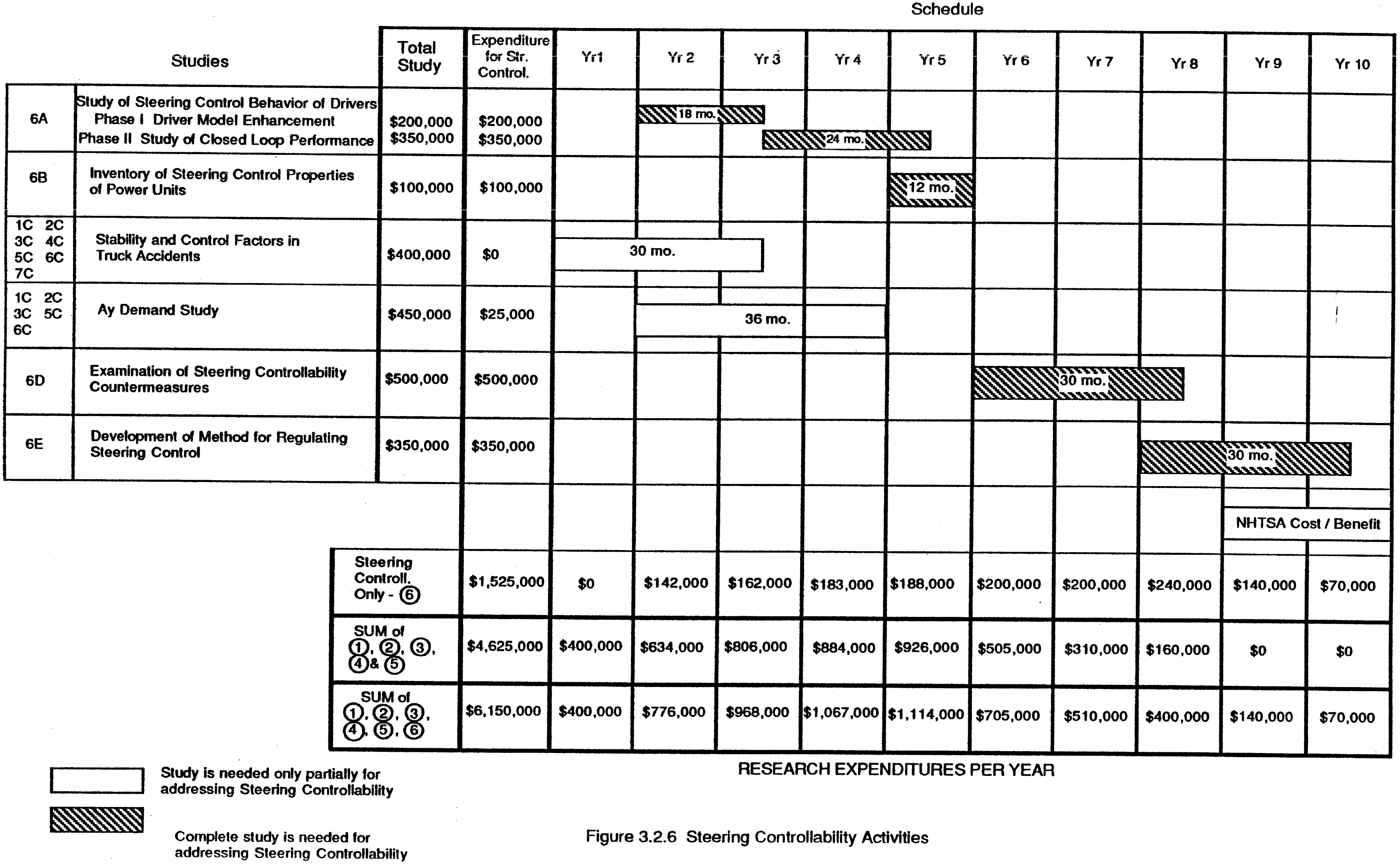
The total of seven projects contributing to the slippery/controllability research effort is estimated to cost $1,000,000 over an 8-year period with the major expenses devoted to countermeasures and regulatory methodology. Because this subject area focuses upon a component (the tire) rather than upon the vehicle system as whole, the research program is quite different from that of other subjects and includes a large expenditure on "exclusive" studies.

Steering Controllability of the Power Unit

The research under the steering controllability subject area addresses all those features of the vehicle which render the driver capable of steering the truck or tractor along a desired path. The problem area is complex and the research addresses fundamental controllability issues which are not addressed in any other subject area. The project schedule outlined in Figure 3.2.6 covers the following studies:

- a study of the interaction between the truck driver and the vehicle in the steering task. The study would be conducted in two phases, namely, (1) driver/vehicle experiments in conjunction with refinement of an analytical model of the driver's steering behavior, and (2) a study of the steering performance of a sample of drivers, with supporting analyses to show the influence of vehicle properties on driver/vehicle system performance.

⑥ Steering Controllability of Power Unit



	Studies	Total Study	Expenditure for Str. Control.
6A	Study of Steering Control Behavior of Drivers Phase I Driver Model Enhancement Phase II Study of Closed Loop Performance	$200,000 $350,000	$200,000 $350,000
6B	Inventory of Steering Control Properties of Power Units	$100,000	$100,000
1C 2C 3C 4C 5C 6C 7C	Stability and Control Factors in Truck Accidents	$400,000	$0
1C 2C 3C 5C 6C	Ay Demand Study	$450,000	$25,000
6D	Examination of Steering Controllability Countermeasures	$500,000	$500,000
6E	Development of Method for Regulating Steering Control	$350,000	$350,000

		Yr1	Yr 2	Yr 3	Yr 4	Yr 5	Yr 6	Yr 7	Yr 8	Yr 9	Yr 10
Steering Controll. Only - ⑥	$1,525,000	$0	$142,000	$162,000	$183,000	$188,000	$200,000	$200,000	$240,000	$140,000	$70,000
SUM of ①, ②, ③, ④ & ⑤	$4,625,000	$400,000	$634,000	$806,000	$884,000	$926,000	$505,000	$310,000	$160,000	$0	$0
SUM of ①, ②, ③, ④, ⑤, ⑥	$6,150,000	$400,000	$776,000	$968,000	$1,067,000	$1,114,000	$705,000	$510,000	$400,000	$140,000	$70,000

RESEARCH EXPENDITURES PER YEAR

Figure 3.2.6 Steering Controllability Activities

- a separate sampled inventory of trucks and tractors to permit estimation of the relevant properties of vehicles in the U.S. fleet. This inventory project is defined as a stand-alone exercise whose precise data needs will not be laid out until completion of the driver/vehicle research, above.

- the accident data study will include examination of the accident record for evidence of steering controllability as a causal element. The types of accidents and environmental conditions most likely to be involved will be defined from the driver/vehicle studies, above, and their associated analyses.

- the data-logging study will yield acceleration data which can be used to estimate the likelihood of the conditions which make severe demands upon steering controllability. Again, the data collection effort has been front-loaded onto the plans presented previously such that only a small additional analysis task is needed for addressing steering controllability.

- the countermeasures which achieve a high level of steering controllability performance are defined and evaluated. The evaluation considers all of the competing aspects of performance in the design of trucks and tractors. The practical and effective countermeasures are delineated for study in the cost/benefit analysis.

The total set of research projects needed in the steering controllability area covers a period of 9.5 years and includes the largest investment in efforts exclusively related to one topic. At the same time, the knowledge base on this subject will be substantially advanced by the front-loaded studies which address the link to safety. Moreover, the outlined research pursues a subject which is seen as having great potential significance, although much needs to be learned. The total expenditure on research for steering controllability amounts to $1,525,000.

Damping of Oscillatory Yaw Motions

Shown in Figure 3.2.7 is a plan for research on the subject of the damping of oscillatory yaw motions. This research addresses, primarily, the small-amplitude lateral motions exhibited by trailing elements in response to random disturbances. The motions warrant attention, from a safety point of view, because trailers may encroach laterally to the point of collision with other vehicles or fixed objects or an unstable roll response may ensue. Also, such motions are perceived with alarm by other motorists who are adjacent to the oscillating vehicle. The envisioned research involves the following individual studies:

⑦ Oscillatory Yaw Motions

Schedule

	Studies	Total Study	Expenditure for Osc. Yaw.	Yr1	Yr 2	Yr 3	Yr 4	Yr 5	Yr 6	Yr 7	Yr 8	Yr 9	Yr 10
7A	Study of Oscillatory Responses	$200,000	$200,000				▨	▨ 24 mo.	▨				
2B 3B 4B 5B 7B	Inventory of Yaw Response Properties in U.S. Trucks	$225,000	$50,000					☐ 12 mo.					
1C 2C 3C 4C 5C 6C 7C	Stability and Control Factors in Truck Accidents	$400,000	$25,000	☐	☐ 30 mo.	☐							
7D	Examination of Countermeasures to Oscillatory Motions	$250,000	$250,000						▨ 24 mo.	▨			
7E	Development of Method for Regulating Oscillatory Motions	$300,000	$300,000							▨	▨ 30 mo.	▨	
												NHTSA Cost / Benefit	NHTSA Cost / Benefit
	Oscillatory Yaw Motion Only - ⑦		$825,000	$10,000	$10,000	$5,000	$50,000	$150,000	$175,000	$185,000	$120,000	$120,000	$0
	SUM of ①, ②, ③, ④, ⑤ & ⑥		$6,150,000	$400,000	$776,000	$968,000	$1,067,000	$1,114,000	$705,000	$510,000	$400,000	$140,000	$70,000
	SUM of ①, ②, ③, ④ ⑤, ⑥ & ⑦		$6,975,000	$410,000	$786,000	$973,000	$1,117,000	$1,264,000	$880,000	$695,000	$520,000	$260,000	$70,000

RESEARCH EXPENDITURES PER YEAR

☐ Study is needed only partially for addressing Oscillatory Yaw Motions

▨ Complete study is needed for addressing Oscillatory Yaw Motions

Figure 3.2.7 Activities on Oscillatory Yaw Motions

- a study of the mechanics of oscillatory motions. The small oscillations seen on doubles and triples will be examined to identify nonlinear mechanisms that permit limit cycle motions. The range of vehicle configurations exhibiting underdamped oscillations will be studied and the parametric sensitivities of their motion behavior will be evaluated.

- the sampled inventory of the truck population will include the collection of data pertaining to oscillatory motions, given the parameters which were found to be important, above.

- the accident data study will be augmented with a search for accidents which may have implicated oscillatory motion behavior.

- design and operational factors will be considered in identifying countermeasures to oscillatory motions. The effectiveness and practicality of each candidate countermeasure will be evaluated to arrive at a set of approaches warranting study in the cost/benefit analysis.

- a method for regulating the damping levels of oscillatory yaw motions will be developed.

The total set of five research studies involves an estimated cost of $825,000 and is shown spanning a period of nine years. At the bottom of the chart shown in Figure 3.2.7, the sum of the year-by-year costs estimated for conducting the overall program of research is shown. As indicated, the total program costs $6,975,000, with the annual outlay peaking in the fifth year.

Appendix A
Brief Project Statements from the Recommended Plan of Research

In this appendix, a brief outline of each recommended research project will be presented. Each project which is designed to provide information exclusively to meet the needs of one vehicle performance area will be simply outlined as a stand-alone research endeavor. Each of the so-called common projects which are designed to address the needs of multiple performance areas will appear with designations of the respective performance area and knowledge base cells which are to be included in the project design. The "common" projects will be presented only under the first, or highest priority, performance area under which they are recommended. The tasks of these studies which address other performance areas will be specifically identified in the outline for each such project.

The coded entry for each project reflects the coordinates of each cell of the research plan shown in the text as Table 3.1.1. The vehicle performance areas were assigned numbers as follows:

No. 1 ---------- Roll Stability
No. 2 ---------- Rearward Amplification
No. 3 ---------- High-Speed Offtracking
No. 4 ---------- Low-Speed Offtracking
No. 5 ---------- Control Under Slippery Conditions
No. 6 ---------- Steering Controllability of the Power Unit
No. 7 ---------- Damping of Oscillatory Yaw Motions

The elements of the information base which are to be satisfied in addressing each performance area are as follows:

Item A -------- Definitions of Response Phenomena
Item B -------- Inventory of the Truck Fleet
Item C -------- Demonstrations of the Link to Truck Accidents
Item D -------- Determination of Practical Countermeasures
Item E -------- Development of Regulatory Procedures

While much elaboration is, of course, required in order to fully define each project, the outlines presented here are intended to at least document the nature of the work needed on each subject.

Projects Initiated Under Subject No. 1, Roll Stability.

Project 1Aa (also addresses 2Aa) [Note that the additional designation, a, after 1A- and 2A- indicates that more that one project is planned for each of these two cells of the matrix. The objectives, rationale and method of this particular research study will be outlined below, with the specific tasks addressing the respective 1A- and 2A- subject areas discussed under the statement of "Methods".]

Title : "Mechanics of Dynamic Rollover"

Objectives: To examine the dynamic phenomena which determine the propensity for vehicle rollover as a result of tripping on curbs and other obstructions, dynamic motions of the payload, vertical excitation at the roadside, and transient lateral acceleration inputs. The transient lateral acceleration category will also cover excitations due to rearward amplification.

Rationale: The focus of prior work in truck roll stability has been on static phenomena and, specifically, on rollover in a steady turn. Since static stability level is a favored measure for formulation of a practicable standard on roll stability, there is a need to examine dynamic phenomena in order to assess the adequacy of a static-only specification. Concerning rollover stimulated by rearward amplification, there is a need to expand the study of rearward amplification to account for the frequency-dependent nature of the rollover response.

Methods: Computerized simulations would be used in studying the various transient roll phenomena. Specialized tire tests are done to characterize the nature of tire side forces developed when the tire side-slips into, say, a curb. Upon defining the vehicle properties which determine transient roll response, computerized simulation would be used to identify any conflicts posed by the desire for both static and dynamic roll stability . Ranges of design parameters serving to benefit both static and dynamic roll stability would be defined for guiding the formulation of a comprehensive roll stability specification.

The task addressing subject 2A would consider the dynamic roll excitations arising due to rearward amplification (which tend to roll over the rearmost trailer in a multi-trailer combination). The computer simulation of this particular phenomenon will focus on the frequency ranges in which rearward amplification maximizes and will identify the vehicle properties influencing roll stability under this particulary dynamic condition.

Costs: The project would require 24 months and cost an estimated $150,000, of which $125,000 is front-loaded onto subject area 1A.

Project 1Ab (also addresses 2Ab)

Title: Driver Factors in Maneuvers Causing Rollover

Objectives: To identify certain generalizeable aspects of truck driver behavior under maneuvering conditions which threaten rollover. In behalf of simple, or quasi-static, conditions leading to rollover, the focus will be upon the driver's ability to sense an impending rollover. The ultimate objective, in these cases, will be to identify the cues which are effective in improving this sensory ability. The objective relative to rollovers induced by rearward amplification is (a) to identify the conditions in which the needed types of steer inputs may be applied and (b) to establish the ability of a cross section of drivers to apply such inputs.

Rationale : The research which has been done examining the mechanics of roll stability, from a vehicle point of view, has been based upon the hypothesis that the inherent stability level of the vehicle serves as a predictor of rollover accident involvement. Another major aspect of the rollover phenomenon, however, involves the driver and his role in either "causing" the types of maneuvers which result in rollover or, conversely, avoiding such maneuvers with the aid of certain sensory skills and judgments. One outcome of the planned research is to better define what the driver can and cannot be expected to do in avoiding rollover. Another outcome will be to identify those vehicle properties which are instrumental in providing beneficial feedback to the driver. Such feedback properties could be promoted in improved vehicle design practice or, conceivably, included as a requirement in a safety standard.

Methods : The core of this research project is a carefully planned set of driver/vehicle experiments in which maneuvering conditions approaching rollover are involved. A sample of real truck drivers would be enlisted to drive in such experiments, with the test exercise designed to address the crucial items of driver instruction, practice, motivation, feedback, safety protection, etc. This exercise will be very difficult and should be built on the extensive experiences of many other such projects undertaken with passenger cars and reported in the open literature. Vehicles incorporating differing "feedback" characteristics would be employed in an attempt to identify those characteristics which help the driver to anticipate his vehicle's rollover limit.

Task 2Ab of the study would focus on the driver's steering control of doubles combinations, with an emphasis on his potential for steering to excite rearward amplification. Situations requiring evasive steering maneuvers would be contrived and the actions of the driver observed in order to put a firmer basis upon the open-loop study of rearward amplification.

Costs: The total study is estimated to cost $300,000, of which $225,000 is front-loaded onto the rollover subject area. The term for the total job is 24 months.

Project 1B

Title: "Inventory of Roll Stability in the U.S. Trucking Fleet"

Objectives: To describe the distribution of roll stability levels prevailing in the U.S. trucking fleet, given the way trucks are equipped and loaded in normal service.

Rationale: In order to analyze either (a) the need for a regulation constraining roll stability level, or (b) the potential impact of defining a given performance level as a requirement for compliance, one needs an estimate of the distribution of roll stability levels prevailing, today, in the trucking fleet. Knowing how roll stability levels are distributed across the population will establish, for example, whether dramatically low "outliers" exist and will enable projection of the number of vehicles which would be affected by the setting of a certain compliance level.

Methods: A plan would be drawn up for obtaining a meaningful sample of field data describing the trucking fleet. A methodology would be developed for making practical field measurements of roll stability characteristics on trucks stopped at roadside inspection stations. The methodology would include a crude experiment, taking a few minutes on each vehicle, for estimating the height of the center of gravity. This experiment would involve the use of individual wheel scales to measure tire loads with the vehicle both level and tilted slightly in roll due to blocks placed under the tires on one side. The tilting exercise serves to develop an incremental load transfer revealing the approximate height of the c.g. Observations would also be made for logging certain features of the suspensions, frame elements, and tires. Subsequent analysis of the field data, as supplemented by available measurements on common suspensions, would yield an estimate of the static rollover threshold on each sampled vehicle. Per the sampling plan, the analyzed results would be expanded to approximate a national distribution.

Costs: The total project is estimated to cost $350,000 and the overall term is 18 months.

Project 1Ca (also addresses 2Ca, 3Ca, 4C, 5Ca, 6Ca, 7C)

Title: Stability and Control Factors in Truck Accidents

Objectives: To compile and analyze information from available accident data which reveals the correlation between the stability and control features of trucks and the types and frequency of their accident involvement. Also, to follow up sampled accident cases, gaining additional information which enriches the data base for studying the involvement of individual vehicle factors.

Rationale: The prospect of improving the safety of trucking by means of upgrading stability and control factors hinges strongly upon the demonstration of links between existing performance properties and accident involvement. While conclusive demonstrations using accident data may not be an absolute requirement for regulatory action to proceed, there is a clear need for a rigorous study of the links which can be made. New methodology for supplementing existing data with case-by-case followup offers a means for improving the "rigor" beyond the mere statistical processing of accident data files. This large study is to employ the most effective means known today for exposing the links that exist between truck accidents and the entire spectrum of vehicle performance attributes which have been defined.

Methods: The mass accident files compiled by BMCS, the NHTSA FARS and NASS systems, and certain key states will be employed as the primary data bases from which to examine links to vehicle characteristics. The crucial step needed to make this effort fruitful involves the case-by-case follow-up to individual accidents in order to obtain supplemental information. Recent accomplishments show that this approach is a promising means for expanding upon mass-reported data. Also, it will be necessary to estimate vehicle properties given knowledge which has accumulated from studies of vehicle mechanics. The compilation of accident counts in correlation with vehicle properties will necessarily involve a variety of such simplified estimations and assumptions. The nominal success already achieved in relating roll stability level to rollover accident involvement in the BMCS file indicates that progress can be made when the analysis is carefully focused.

Tasks specific to area 1Ca will attend to a refinement of the previous analysis of the BMCS file relating rollover accidents to a computed value of rollover threshold for tractor-semitrailers. Supplemental data will be needed in order to better estimate the approximate height of the payload center of gravity in vehicles suffering rollover. Other accident data files may also be used in generating analogous relationships as a check on the findings obtained from the analysis of BMCS data.

The task devoted to the rearward amplification subject, area 2Ca, will focus on rear trailer rollovers and the private and public data sets which might provide evidence of this type of incident. The primary data files in the private arena are those maintained by individual trucking fleets -- some of which are known to be highly definitive in describing each accident. Such data files will be supplemented with follow-up efforts which intend to gain more information about the vehicles involved and the conditions precipitating the rollovers.

The task devoted to high-speed offtracking, area 3Ca, will focus upon accidents which suggest that high-speed offtracking has occurred. Such events would include all turning accidents in which the trailer may have struck some vehicle or fixed object on the outside of the curve.

Accident potential due to low-speed offtracking at intersections will be explored in a preliminary way through a current FHWA-sponsored study which will delineate the types of conflict which occur [1]. Follow-up research should take the lead from this effort, seeking to identify accidents which appear to have resulted from these types of conflict.

In order to address accidents involving loss-of-control due to insufficient tire traction on slippery surfaces, area 5Ca, there is a need to study, at least, single-vehicle accidents occurring on wet pavements to determine which incidents may have taken place due to, say, hydroplaning or some other gross deficiency in traction level. Again, supplemental data to that provided in the mass data files will probably be needed. A recently completed FHWA-sponsored study on truck accidents at interchanges showed that hard-copy police reports served rather effectively for identifying accidents of this type at one peculiarly troublesome site [2].

The task examining accidents which may be germane to steering controllability, area 6Ca, should be better defined following completion of the driver control experiments and analyses planned for project 6A. Accidents which may be candidates for inclusion in this set will be a broad class of loss-of-control events in which the driver was clearly unable to steer to retain the desired path--even though the pavement was, say, dry and brake lockup did not precipitate the control loss.

Accidents involving oscillatory responses, area 7C, can only be studied with the aid of fairly detailed incident reporting and, perhaps, follow-up. The outcome of such accidents may be collisions, run-off-road events, or rollover. The connection of such outcomes with oscillatory behavior may be demonstrated only with a high level of description of the involved vehicles plus eyewitness indications that oscillations were involved.

Costs : The total project is estimated at $400,000, of which $250,000 is front-loaded onto the rollover subject area. The overall term of the total project is 30 months.

Project 1Cb (also addresses 2Cb, 3Cb, 5Cb, and 6Cb)

Title : Acceleration Demands Imposed Upon Heavy-Duty Trucks

Objectives: To obtain and analyze data indicating the probability distribution of acceleration demands which truck drivers impose upon their vehicles in everyday service. Also to obtain ancillary data accompanying the acceleration recordings in order to define the operating conditions which influence these distributions.

Rationale: Truck drivers operate their vehicles in a manner which imposes varying demands on response quality from moment to moment. The levels of braking and cornering accelerations which are demanded of the vehicle can be looked upon as covering a range of values, with some portions of the range being more frequently encountered than others. Measurements of such acceleration demands with passenger cars have led to a recent analysis effort in which the likelihood of a certain class of loss-of-control event can be predicted.[3] Further, this prediction technique shows how the likelihood of such events will change as a result of variations in certain key vehicle properties. This study of truck accelerations offers to make a large sample of acceleration demand measurements on heavy-duty vehicles so that subsequent analyses of such data can provide predictors of certain types of truck accidents involving loss-of-control.

Methods: A data-logging instrumentation system will be assembled and a procedure for its use will be developed and demonstrated in a pilot exercise. Subsequently, a sample of commercial vehicle operations will be selected for the collection of data using the logging system in normal trucking service. Data collection will cover differing vehicle configurations, drivers, types of trucking service, and regions of the country. Recordings of the measured acceleration responses will be retrieved from the on-board instruments and returned to the laboratory for computerized analysis. The data will be analyzed to predict the likelihood that acceleration demand will exceed vehicle performance limits in each of the respective modes of loss-of-control. This "likelihood" prediction will relate differing performance limits to the probability of control loss, thereby connecting each vehicle performance area to a corresponding aspect of accident production.

Task 1Cb of this study will involve preparation of a data analysis scheme which will predict the likelihood of rollover, given the value of the vehicle's inherent rollover threshold.

Task 2Cb will involve an analysis method which predicts the likelihood of a rear-trailer rollover due to rearward amplification in a multi-unit-vehicle combination. Such an analysis will require treatment of both amplitude and frequency information from the in-vehicle recordings.

Task 3Cb involves prediction of the probability distribution of high-speed offtracking responses when the vehicle is operating in a curve. The results of this analysis would be coupled with measurements in Project 3Cc which will establish the distribution of actual lateral positioning which trucks assume in travelling around curves on both the open road and on interchange ramps. Together, both sets of data would be used to compute the likelihood that outboard offtracking would be developed to a sufficient degree to cause collision with outboard curbs, parked vehicles, or other fixed objects whose typical position adjacent to the roadway can be stated. Again, the "likelihood" projection would show the continuous influence of high-speed offtracking properties on the probability of a collision or tripping outcome.

Task 5Cb would involve analysis of the probability that the acceleration demand level would exceed the limits of tire traction capability on slippery surfaces. This analysis would also require estimates of the incidence of aggravating weather and pavement conditions as environmental variables influencing the total probability of such events.

Task 6Cb cannot be defined until the results of the driver/vehicle steering control experiments have been completed. Nevertheless, it is anticipated that the distribution of lateral acceleration demands will be analyzed to predict the likelihood of incidents in which steering controllability is severely challenged. Existing knowledge on the steering control problem also suggests that the time duration of an elevated level of lateral acceleration is another factor that may be included in the predictive analysis.

Costs : The total project is estimated at $450,000, of which $300,000 is front-loaded onto the rollover subject area. The overall term of the total project is 36 months.

Project 1D

Title: Study of Countermeasures to Roll Instability

Objectives: To identify practicable and effective countermeasures to roll instability. Such countermeasures may either improve the rollover threshold level of vehicles or provide better feedback to the driver such that rollover hazards are better anticipated.

Rationale: The study is simply a logical step in developing the base of knowledge for writing a safety standard (or, at least, for consideration of the cost/benefit basis for such a standard). In the case of the roll stability subject, countermeasures which improve rollover threshold level are well defined, conceptually, but work is needed to examine the practical implications of differing avenues of implementation. For example, there is a need in this study to examine the potential conflicts between stiffened suspensions in behalf of roll stability and the desire for good yaw stability of the power unit and good ride quality. These and other practicality issues, as well as projections of the safety benefits associated with each candidate countermeasure, must be examined so that truly viable means of improving performance are identified.

Methods: Candidates for improving roll stability, as well as the sensory feedback properties of vehicles, are developed from the results of all of the research preceding this stage. The candidate countermeasures are evaluated, first, by means of studying field experience gained with any examples of such hardware that may be in current service. Safety effectiveness estimates are made with the aid of engineering analyses and the generalized models of accident probability developed through projects 1Ca and 1Cb. The practicality of countermeasures which have no precedence in the field may require field trials of prototypes and assessments of the supportive technology for implementation. This study concludes by identifying each viable countermeasure, together with the data which will enable a cost/benefit study as a precursor to rulemaking.

Costs: The study is estimated to cost $250,000, and to require a term of 18 months.

Project 1E

Title: Development of a Method for Regulating Roll Stability

Objectives: To develop the technical definitions, measurements, test procedures, and other protocols needed for specifying a motor vehicle safety standard on the roll stability of heavy-duty trucks.

Rationale: This project constitutes the final step in the logical development of information leading to a regulation on roll stability. The study addresses the substantial questions that remain, after all of the preceding research, concerning the best way to actually specify the desired stability qualities.

Methods: The primary effort in this study concerns the development of a test methodology. The most attractive candidate method for measuring the static roll stability of assembled vehicles is the so-called "tilt-table" device. Such a device would be built in this project and the associated test procedure developed as a demonstration of the standards-suitable method. The project must also come to grips with a format in which to characterize and measure the properties of the respective units in multi-element truck combinations. In this regard, it may be necessary to define a "reference semitrailer" for use in compliance-testing truck tractors. Regarding the properties of semitrailers, themselves, it may be that trailer suspensions could be qualified separately such that the diffuse trailer manufacturing industry would only need to address the center of gravity locations as their part of the measurement burden. The overall set of protocols which constitute a model standard would be designed with the aid of engineering analysis and developed in detail so that a complete test procedure is defined. The test procedure would then be applied on a number of illustrative vehicles to demonstrate and refine the compliance test process and to provide a basis for estimating the associated measurement burden.

Costs: The estimated cost is $400,000, to be spent over a 24-month effort.

Projects Initiated Under Subject No.2, Rearward Amplification

Project 2B (also addresses 3B, 4B, 5B, 7B)

Title: Inventory of Yaw Response Properties in the U.S. Trucking Fleet

Objectives: To develop base data and conduct analyses estimating the distribution of specific yaw response properties of U.S. trucks. The yaw response properties of interest cover the respective subject areas, viz., No.3, High-Speed Offtracking, No.4, Low-Speed Offtracking, No.5, Control Under Slippery Conditions, and No. 7, Damping of Oscillatory Yaw Motions.

Rationale: The distribution of yaw response properties in the truck population must be known in order to project the impact of prospective changes in vehicle performance. In the yaw response areas included for study here, a modest number of vehicle features need to be known for a meaningful estimation of response characteristics to be accomplished. Such properties can be determined through very simple inspection of vehicles at the roadside. To the degree that the gathered data sample is statistically representative, subsequent analyses can project the changes which rulemaking would impose on the national fleet. Likewise, potential safety benefits can be estimated, on a national scale, when prospective changes in performance are linked to accident rates using the distribution information developed in this study and the models of accident probability developed in Projects 1C and 2C.

Methods: A data collection methodology, together with a sampling scheme, would be developed and then applied in a field data collection exercise. The in-field measurement would be confined primarily to gross geometric dimensions plus observations of basic suspension types and tire construction and tread depth. Axle loading data on each sampled vehicle would, presumably, be obtained by situating the measurement activity adjacent to a roadside weigh-scale facility. The gathered data would be analyzed with the aid of existing files of suspension and tire performance information, together with computerized simulation, in order to define the approximate yaw response properties of each sampled vehicle. Given the sampling scheme used in collecting the field data, then, the distribution of yaw response properties in the overall truck population would be estimated..

The aspect of the project pertaining specifically to Project 2B, rearward amplification, involves the analytical method for estimating rearward amplification level using the relatively crude data obtained in the field exercise. In this regard, available data on tires and inertial properties will be used to supplement the measured quantities to permit the final estimations to be computed. Likewise, the tasks addressing items 3B, 4B, 5B, and 7B involve simplified analyses which employ the field data, supplemented by available data on the mechanics of components, to project the respective vehicle performance properties.

Costs: The total cost of this project is estimated at $225,000, of which $100,000 is front-loaded onto the rearward amplification program. The total project term is 18 months.

Project 2D (also addresses 3D and 4D)

Title: Examination of Trailing Fidelity Countermeasures

Objectives: To identify practicable and effective countermeasures to each of the various problems of trailing fidelity without unduly compromising performance in the other areas.

Rationale: The development and evaluation of countermeasures is, again, a logical step in the process leading toward a possible regulatory package. In the case of the three subjects covered under this study (rearward amplification, high- and low-speed offtracking), there are known conflicts in which classical means of improving one quality will generally, but not always, produce degradations in the others. All of the means of possibly improving each of the three vehicle characteristics must be examined from the viewpoint of mechanical performance as well as the practicable issues of service in the field.

Methods: Candidate countermeasures are first defined given classical innovations attempted by the industry as well as those which are identified from research efforts. The effectiveness of individual approaches, in terms of mechanical performance characteristics, will be assessed by means of engineering analysis. Those countermeasures which are found to be broadly beneficial across both amplification and offtracking areas of performance would be implemented in prototype form, where feasible, and introduced into field testing. Practical issues involving the usage of the prototype hardware would be assessed in actual service. Analyses would be conducted to project the net safety benefits which would accrue from adoption of each of the various countermeasures. Those countermeasure concepts which are judged viable for commercial application are fully documented with the data needed for conducting a subsequent cost/benefit analysis leading toward rulemaking.

Costs: The total cost of this project is $400,000, of which $300,000 is front-loaded onto the rearward amplification project. The total term of the project is 30 months.

Project 2E

Title: Development of a Method for Regulating Rearward Amplification

Objectives: To develop the technical definitions, measurements, test procedures, and other protocols needed for specifying a motor vehicle safety standard on the rearward amplification response of multi-unit truck combinations.

Rationale: The rearward amplification behavior of the vehicle must be quantifiable in objective terms using a test method, with associated protocols, in order to specify requirements for compliance. This project will develop the generalized concept by which this combination vehicle property can be specified, given only a set of specifications applying to the respective units that would make up a combination vehicle. (Although this goal of individual specifications for, say, tractors, trailers, dollies, etc., is to be sought, it may prove infeasible such that a means of regulating the entire vehicle combination in service must be developed.)

Methods: The conceptual development of differing compliance tests would be conducted first by means of vehicle simulation and supporting analysis. When a viable concept has been defined for specifying and measuring the performance of either individual units or the whole vehicle combination, the detailed procedure for compliance testing would be developed. Needed prototype test apparatus would be constructed and the procedure would be applied on a sample of vehicles in order to demonstrate the method and to provide an exercise from which to evaluate probable costs of compliance testing.

Costs: The estimated cost is $300,000 and the nominal term is 24 months.

Projects Initiated Under Subject No. 3, High Speed Offtracking

Project 3A (also addressees 4A)

Title: Study of the Mechanics of Offtracking

Objective: To elucidate the nature and parametric sensitivities of the transient offtracking behavior of articulated truck combinations operating at highway speeds. Also, to examine the influence of differing spread axle arrangements on both high speed offtracking and the cornering behavior of vehicles at low speeds, especially on low-friction surfaces.

Rationale: Regarding transient, high-speed offtracking behavior, recent observations made during full-scale vehicle testing indicate that there may be substantial overshoots in the outboard offtracking paths of trailer axles if a curve is entered abruptly. That is, a peak value of outboard offtracking may occur, under transient conditions, which is much further outboard than the steady state excursions which have been addressed previously. This phenomenon may render high-speed offtracking a more important safety issue than earlier believed due to the greater outboard excursions which threaten curb strike or other collisions involving the rear of the trailer(s). The low-speed phenomenon of interest involves the problem in which tight-radius turning gives rise to lateral slip on vehicles having spread, non-steerable axles. Although this matter is understood, conceptually, a parametric sensitivity analysis is needed to sort out the range of vehicle designs in which control problems would arise.

Methods: Engineering analysis, using computerized simulations, would be used to explore the high- and low-speed offtracking phenomena cited above. Full scale tests would be undertaken to confirm and demonstrate the control problems which occur with a few of the vehicle configurations which are in common service. Task 3A of this project concentrates upon the high-speed response properties of interest while Task 4A addresses the low-speed phenomena.

Costs: The estimated total cost of this project is $150,000, of which $125,000 is front-loaded on subject area No. 3, High Speed Offtracking. The total project term is 12 months.

Project 3Cc

Title: Study of High Speed Offtracking in Actual Service

Objectives: To determine the statistical distribution of the lateral placement of truck wheel paths on high speed turns, especially expressway ramps. To, thereby, enable an analysis of the probability that vehicles exhibiting a given high speed offtracking characteristic would experience accidents due to outboard-intruding wheelpaths.

Methods: A field experiment would be designed in which an instrument system would be applied for measuring the lateral placement of truck tires as the vehicle passed through a curve of known geometry, shoulder and barrier treatment, etc. A substantial number of curve sites would be selected including curves located on main line roadways and at expressway ramps. The curve sections would be selected on the basis of a sampling scheme intended for representing typical truck operations across the U.S. The collected data would be analyzed, together with the supplemental information on the curve sites, themselves, to render a distribution of the lateral placement of truck wheel paths on differing types of curves. An analysis would then be conducted, relating the level of high-speed offtracking performance of individual vehicles to the likelihood that such vehicles would become involved in accidents of this peculiar type.

Costs: The total cost of this project is $200,000 and the term of the study is 18 months.

Project 3E

Title: Development of a Method for Regulating High-Speed Offtracking

Objectives: To develop the technical protocols needed for specifying a motor vehicle safety standard on the high-speed offtracking performance of truck combinations.

Rationale: A regulatory method would be developed if the study of accidents and the estimation of accident probability indicated that substantial warrants exist for regulating high-speed offtracking. If this is the case, the study is needed to determine a reasonable means of assuring good high-speed offtracking performance, recognizing that multiple manufacturing parties are involved in the construction of articulated vehicle combinations.

Methods: Engineering analysis would be needed to screen various ways of specifying, say, the respective attributes of the tractor, trailer, and dolly elements of a combination. A test procedure would be developed for determining the compliance of vehicles with such a specification. The selected approach would be demonstrated by applying it to a number of vehicles, including samples which were modified to exhibit improved performance, per the effective countermeasure schemes found in Project 3D.

Costs: The estimated total cost is $200,000 and the project term is 12 months.

Project Initiated Under Subject No. 4, Low-Speed Offtracking

Project 4E

Title: Development of a Method for Regulating Low-Speed Offtracking

Objectives: To develop the technical protocols necessary for a motor vehicle safety standard on low-speed offtracking.

Rationale: Although low-speed offtracking is a response characteristic that derives primarily from the size and weight laws which are written, the designers and operators of heavy-duty vehicles do have some leeway in influencing low-speed offtracking properties. The envisioned standard might simply constrain low-speed offtracking to the maximum which is currently practiced in road-legal vehicles, and would constitute a formal "bottom line" beyond which any liberalized size allowances would impose undue burden on the U.S. road system. A "safety" standard may be warranted by the fact that the offtracking behavior of our current tractor-and-48-foot-semitrailer combination appears to have taxed the geometric allowances of the road system to its limits.

Methods: The methodology for measurement of low-speed offtracking is straightforward and may simply need the formalization of certain procedural details, with the aid of engineering analysis. More importantly, since offtracking is truly a property of the total vehicle combination, a method is needed for specifying the behavior of the total vehicle whose elements are manufactured by various parties.

Costs: The total cost of the project is estimated at $50,000 and the term is 12 months.

Projects Initiated Under Subject No. 5, Controllability Under Slippery Conditions

Project 5A

Title: Study of Truck Tire Traction Under Slippery Conditions

Objectives: To collect and analyze data revealing the traction behavior of truck tires on wet pavements. To develop a sound understanding of the role played by hydrodynamic phenomena in degrading the traction performance of truck tires on wet pavement. To provide impetus and direction to industrial research seeking to improve the wet-traction performance of truck tires. To illustrate the operating conditions under which trucks may suffer control problems due to traction deficiencies on wet pavements.

Rationale: Research has indicated that truck tires are generally deficient in wet-traction performance and may even be capable of complete hydroplaning under certain operating conditions on wet pavements. Preliminary accident studies have suggested that trucks may, indeed, be frequently involved in loss-of-control events on certain roadways. Thus, there seems good reason to more closely examine the traction problems experienced with truck tires as a potentially important aspect of the overall truck controllability issue. Since engineering examination of the traction mechanics, themselves, has only been sketchy, there is need for a definitive study on the wet traction matter.

Methods: Measurements of truck tire traction performance would be made, using a special dynamometer suitable for testing truck tires, on differing pavements with varying values of tread depth, velocity, and water depth. The gathered empirical data would be coupled with an analytical model of the tire operating on wetted pavement. The development of an analytical model would be guided by prior modeling efforts of this generic type reported in the open literature. The study would seek to relate the design and operating parameters of the tire to wet traction performance. The results of the study would contribute to development of a traction performance standard for truck tires as well as provide the basis for advisory guidelines to the trucking industry on wet traction problems.

Costs: The total cost of this project is estimated at $200,000, and the total term is 18 months.

Project 5D

Title: Examination of Countermeasures to Loss of Control Under Slippery Conditions

Objectives: To identify effective and practicable countermeasures to the loss-of-control problems which derive from wet-traction deficiencies in the truck tire. The countermeasures may include both design and operating variables involving the application of trucks tires in commercial service.

Rationale: The problem of deficiency in the wet-traction performance of truck tires may call for both innovative changes in tire design as well as simply a greater level of attentiveness to tire usage on the part of the trucking industry. This project is intended to clarify the options and guide the attainment of solutions, whether implemented in safety standards or voluntary practices.

Methods: The analytical model of the wet-traction performance of truck tires would be exercised to define potential avenues of improvement in truck tire design and operation. With the cooperation of the tire industry, prototype improvements in tire tread and/or carcass design could be demonstrated and the effectiveness level assessed through dynamometer measurements. Benefits deriving from improved control over tread depth, inflation pressure, tire load, and/or speed on wet pavements would be quantified and demonstrated for adoption by the trucking industry. Candidate countermeasures which would be practicable for meeting a motor vehicle safety standard would be identified.

Costs: The total cost of this project is estimated at $300,000. The total term of the study is 24 months.

Project 5E

Title: Derivation of a Method for Regulating Controllability Under Slippery Conditions

Objectives: To develop the technical definitions, measurements, test procedures, and other protocol details needed for a motor vehicle safety standard on the controllability of trucks under slippery conditions.

Rationale: Assuming that deficiencies in the wet-traction performance of truck tires are sufficient to warrant regulation, this study develops the technical framework for specifying the requirements for compliance. A supplementary requirement may also be needed in the area of controlling the minimum tread depth or inflation pressure conditions under which truck tires are operated in the field.

Methods: The specification of a traction performance requirement involves a measurement methodology for which precedence exists in the area of tire quality grading for passenger car tires. A test procedure must be developed which addresses the critical areas of need in the traction performance of truck tires and which practicably reflects the state of practice in truck tire traction measurement. The developed test method would be exercised on a sample of truck tires in order to demonstrate the formal procedure and to provide the basis for estimating the burden which compliance testing would impose.

Costs: The total project is estimated to cost $400,000, covering a term of 30 months.

Projects Initiated Under Subject No. 6, Steering Controllability of the Power Unit

Project 6A

Title: Study of the Steering Control Behavior of Drivers (Two Phases)

Objectives: Phase 1 - To obtain a fundamental understanding of driver closure of the steering loop and to express this understanding in the form of an enhanced model of driver control capabilities. Phase 2 - To quantify the influences of the steering performance properties of trucks on the abilities of drivers to control directional response. The overall objective of this study is to develop clear definitions of the ranges of vehicle performance properties that will lead to good steering controllability over the expected ranges of driver control capabilities.

Rationale: Vehicles that are difficult to control are suspected of contributing to (a) situations that require drastic steering actions and (b) the likelihood that an accident will ensue. Also, some heavy trucks that are easy to control under ordinary circumstances may become unusually tricky to handle in an emergency. If this is the case, the driver may not be able to successfully perform evasive actions needed to avoid unforseen obstacles and resolve traffic conflicts. The base of knowledge concerning why and how drivers apply steering control is not sufficient to identify the levels of changes in vehicle properties that would be successful countermeasures for reducing accidents on curved sections of highway or in obstacle-avoidance situations. Hence, a first phase is needed to obtain information on the cues drivers use to adjust steering control and to quantify driver performance in maintaining directional control. Given knowledge of driver skill levels, the influences of changes in vehicle properties on the performance of the driver/vehicle system can be examined and understood.

Methods:

Phase 1. This will be a study of truck drivers. It will require both human factors and control engineering research. Based on research on passenger car driving, some of the driver factors to be considered might be (1) driver sensitivities to path-keeping errors in translational and rotational positions, velocities, and accelerations, (2) the previews that drivers use in planning and adjusting their control actions, and (3) the bandwidths or time periods they need to be able to control vehicles with sufficient accuracy for the space available in traffic.

Phase 2. This phase will employ the results of the first phase to (1) obtain a group of truck drivers with a wide, yet representative, range of driver skills and (2) study the influences of changes in vehicle properties on the driver factors considered in Phase 1. In addition, driver/vehicle studies will be used in Phase 2 to quantify the performance of closed-loop systems composed of (a) selected drivers and (b) vehicles with different levels of steering gain and lateral and rotational response times. The "driver" model developed in Phase 1 will be used to extrapolate from the experimental results obtained in Phase 2.

Costs: The total cost of the project is estimated at $550,000--$200,000 for Phase 1 and $350,000 for Phase 2. Phase 1 will last for 18 months. An additional 24 months will be needed for Phase 2.

Project 6B

Title: Inventory of Steering Controllability Properties of Power Units

Objectives: To describe the distribution of steering controllability properties existing in the U.S. trucking fleet. (A specific definition of "steering controllability properties" requires the completion of Phase 1 of Project 6A. A working definition of these properties includes (a) lateral acceleration gain as a function of lateral acceleration level and (b) response times in yaw rate and lateral acceleration during sudden turns ("J-turns") and obstacle-avoidance maneuvers.)

Rationale: An inventory of steering control properties would be used to assess (a) the need for a steering controllability standard and (b) the impact of selecting a given performance level as a requirement for compliance. An estimate of the distribution of steering controllability properties would establish quantifiable performance bands that characterize poor, typical, and good performance. Clearly, the number of vehicles projected to have especially poor performance would indicate the magnitudes of the changes that would be brought about by a minimum standard.

Methods: A plan for sampling the trucking fleet would be developed. Since steering controllability depends mainly on the characteristics of the truck or tractor and only slightly on the units being towed, this inventory would be directed towards determining the loads carried by the towing units' tires, the type and condition of tires employed, the geometric layouts, and the mass distributions of the towing units. The steering controllability properties would be estimated using the component properties listed above. A few experiments would be conducted to verify the validity of the procedure used to estimate steering controllability levels.

Costs: The total cost of the project is estimated at $100,000 and it would be performed in one year.

Project 6D

Title: Examination of Steering Controllability Countermeasures

Objectives: To assess the relative feasibility, effectiveness, and cost of practical countermeasures for improving the steering controllability of heavy trucks.

Rationale: A study of countermeasures will provide information that can be used to evaluate the operational and economic costs associated with changes that are likely to result from a performance standard on steering controllability. The results of this study will provide descriptions of technically feasible countermeasures, the amounts of improvement in performance associated with various countermeasures, the degree to which manufacturers and operators can be expected to employ various countermeasures, and the costs to the members of the trucking industry. This information is essential for use in making cost/benefit comparisons.

Methods: The results of Project 6A will be used to identify those mechanical properties of heavy trucks that have a significant influence on steering controllability. The identified mechanical properties will be used to guide the selection of a set of countermeasures for further study. Demonstrations of the technical feasibility of the more attractive countermeasures will be made. In cooperation with advice from manufacturers, operators, drivers, and technical committees associated with these groups, the practicality of employing these countermeasures will be evaluated. The following issues will be considered: (a) the likelihood of lowering performance in another safety-related area, (b) whether industry has the technology available to incorporate the countermeasure, (c) the costs associated with changing over to higher performance vehicles, and (d) the generalized economic benefits of operating higher performance vehicles.

Costs: The total cost of this project is estimated at $500,000 and it would take 30 months to complete.

Project 6E

Title: Development of a Methodology for Regulating Steering Controllability

Objective: To define a regulatory procedure that can be used to assess whether a given power unit possesses an acceptable level of steering controllability.

Rationale: A candidate procedure for a performance standard should be well defined so that the implications of applying this standard to the current trucking fleet can be evaluated. Work is needed to ensure that the procedure is objective, repeatable, comprehensive, and yet no more complicated than necessary to evaluate performance. A clearly understandable methodology will provide the basic framework for setting reasonable and justifiable performance levels.

Methods: The results of Project 6A will include the definitions of vehicle maneuvers that challenge vehicle performance related to steering controllability. These maneuvers will be examined to determine the extent to which their outcomes can be predicted by analysis and/or open-loop vehicle tests. The feasibility of using a control trailer concept for testing tractors will be examined. Proposed sets of test procedures and analyses will be formulated and compared. A prototype test/analysis procedure will be applied to a sample of vehicles with poor, typical, and good steering controllability. Closed-loop tests will also be performed on these vehicles to indicate the extent that objective open-loop results predict objective and subjective closed-loop results. A proposed procedure will be defined and demonstrated to interested parties.

Costs: The estimated cost of this project is $350,000. The period of performance would be 30 months.

Projects Initiated Under Subject No. 7, Damping of Oscillatory Yaw Motions

Project 7A

Title: Study of the Mechanics of Oscillatory Yaw Motions

Objectives: To obtain a fundamental understanding of how the mechanical properties of combination vehicles contribute to oscillatory yaw motions of trailing units.

Rationale: Articulated vehicles may have lightly damped, or even unstable, oscillatory modes of yaw motion. The trailing units of doubles combinations often have a lightly damped oscillatory motion that can easily be noticed by drivers. Even if the amplitudes of these oscillations are small, they can appear threatening to the drivers of other vehicles. In addition, a less common, but probably more serious, situation can develop in doubles with extremely rear-biased states of loading. In this case, the unfavorably loaded double becomes increasingly oscillatory as speed is increased and at highway speeds these vehicles can become unstable and uncontrollable. Another type of oscillatory problem is created when special purpose semitrailers are coupled to the rear of heavy trucks through a pintle hitch connection. These special semitrailer-truck combinations may be unstable for reasons similar to those applicable to car-travel trailer combinations. If the conditions leading to oscillatory modes of yaw motion were better understood and clearly defined, one could develop guidelines for safe towing practices and, if need be, safety standards that apply to trailers and are intended to assure adequate damping of yaw motions.

Methods: This project starts with an analytical/simulation study of the three types of yaw oscillations referred to in the "Rationale." Based on the results of the simulations, potentially unfavorable configurations are to be assembled for use in a test/demonstration program that illustrates both (a) the oscillatory performance of the unmodified combinations and (b) the amount of damping that can be achieved through technically feasible countermeasures. These test and analytical results will be assembled into an information package defining (a) the vehicle and operational conditions that lead to oscillatory yaw behavior and (b) the vehicle and operational countermeasures that furnish a level of damping that will provide adequate safety margins.

Costs: The estimated cost of this project is $200,000 and it will take 24 months to complete.

Project 7D

Title: Examination of Countermeasures to Oscillatory Motions

Objectives: To evaluate the practicality of technically feasible countermeasures identified from the results of Project 7A.

Rationale: To be satisfactory, countermeasures for reducing oscillatory behavior should not (a) significantly degrade other aspects of vehicle performance, (b) entail overly costly vehicle modifications, or (c) reduce productivity more than a reasonably small amount. The purpose of this project is to examine technically feasible countermeasures with respect to items (a), (b), and (c) listed above.

Methods: The results of Project 7A will provide an initial set of technically feasible countermeasures for reducing oscillatory yaw motions. The implications of implementing these countermeasures into trucking operations will be estimated with regard to safety considerations, operational benefits or problems, and economic concerns. A simulation and testing program will be used to find out if countermeasures based on reducing oscillatory motions degrade other aspects of vehicle performance. The operational benefits of using non-oscillatory combinations will be examined by interacting with trucking firms and, if possible, by modifying vehicles in-service for use in a demonstration project. An economics/engineering study will be conducted to evaluate the costs and effectivenesses of various countermeasures.

Costs: The estimated cost of this project is $250,000 and it will take 24 months to complete.

Project 7E

Title: Development of Methods for Regulating Oscillatory Motions

Objectives: To develop guidelines and test procedures that can be used to assess the level of damping involved in oscillatory modes of yaw motion.

Rationale: As with all regulatory methods, a candidate procedure for a performance standard should be well defined so that it can be evaluated by the trucking industry. In the case of oscillatory motions, regulations may need to be accompanied by, or contain, guidelines for matching towing units to trailers. Due to the need to regulate both trailers and tractors, work is needed to decide on objective, repeatable, and practical procedures for testing and/or analyzing both towing and towed units.

Methods: The practicality of using "control" vehicles to test semitrailers and full trailers will be investigated in a pilot test program that will be developed through a simulation study. Analyses will be performed to see if towing unit guidelines (possibly based on the mass distribution, hitch location and loading, and tire properties of the towing unit) will be sufficient for regulating towing units suitable for pulling particular classes of trailers. The results of these analyses will be challenged in a test program involving a "variable characteristics" tractor-semitrailer. Also, tests will be performed with a variable characteristics double. Based on the results of the tests and analyses performed in this project, an objective test procedure for evaluating yaw damping will be developed.

Costs: The estimated cost of this project is $300,000 and it will take 30 months to complete.

References

[1] A currently active research study entitled, "The Operation of Larger Trucks on Roads and Streets with Restrictive Geometry" sponsored by the Federal Highway Administration; contractor is Goodell-Grivas, Inc., Southfield, Michigan.

[2] Ervin, R.D., et al, "Impact of Specific Geometric Features on Truck Operations and Safety at Interchanges" UMTRI, August 1985. 2v. Report No. UMTRI-85-33/1.

Sponsored by the Federal Highway Administration. Contract No. DTFH61-82-C-00054.

[3] Ervin, R.D., and Winkler, C.B., "Estimation of the Probability of Wheel Lockup" (Presented at the Third International Association of Vehicle Design Congress on Vehicle Design and Components, March 3-6, 1986, Geneva, Switzerland.).