CHAPTER 5

SAFETY AND TRAFFIC OPERATIONS

INTRODUCTION

Safety was a primary consideration evaluated in this Study, which responds to the Department's enhanced priority on safety -- its preeminent goal -- as well as the considerable public concern about mixing larger trucks with passenger cars on our highways. The TS&W policies directly influence the stability and control characteristics of trucks when they operate at or near established size and/or weight limits. These characteristics influence how easily a truck driver can maintain control should operating conditions become challenging or regain control should it be lost in response to a precipitous event. Although to date safety has not been an explicit objective of TS&W policy in the United States, safety can be significantly affected either positively or negatively by changes in truck design features that result from policy changes. Table V-1 shows qualitatively the relative positive and negative effects of increases in dimensions, weights and loading conditions, and operations on crashes involving trucks and certain vehicle stability and control measures.

TRENDS IN MEDIUM TO HEAVY TRUCK CRASH EXPERIENCES

Medium to heavy trucks account for approximately 3 percent of vehicles in use on the Nation's highways and accumulate 7 percent of all the vehicle miles of travel (VMT), while being involved in 8 percent of all fatal crashes and 3 percent of all crashes (fatal, injury-producing, and property-damage-only crashes). Medium weight trucks have GVW ratings between 10,000 and 26,000 pounds, while heavy trucks weigh in excess of 26,000 pounds. The relative involvement of medium to heavy trucks in fatal crashes has decreased over the past 8 to 10 years.

In 1995, 4,903 people were killed (see Table V- 2) and 119,000 injured in crashes involving medium to heavy trucks, the majority (78 percent) of those killed were occupants of other vehicles involved in collisions with medium to heavy trucks. Most fatal crashes occur on rural roads (66 percent) and involve single-trailer combinations (68 percent) (see Figure V-1).

Table V-1
Safety Impacts of TS&W Limits and Truck Operation

Vehicle Features		Crash Occurrence		Vehicle Stability		Vehicle Control		
		Likelihood	Severity	Static	Dynamic	Braking	Low Speed Offtracking	High Speed Offtracking
Size	Length	- e	--	+ E	+ E	--	- E	+ E
	Width	- e	--	+ E	+ E	--	- e	+ e
	Height	--	--	- E	- E	--	--	- e
Design	Number of Units	- e	- E	--	- E	- e	+ E	- E
	Type of Hitching	--	+ e	+ E	+ E	+ e	+ e	+ E
	Number of Axles	--	--	+ e	+ e	+ E	+ e	+ e
Loading	GVW	- e	- E	- e	- E	- E	--	- E
	Weight Distribution	- e	- e	- e	- E	- E	--	- e
	Center of Gravity Height	- e	- e	- E	- E	- E	--	- e
Operation	Speed	- E	+ E	- e	- E	- E	+ E	- E
	Steering Input	- e	- e	- e	- E	- E	- E	- E

+ / - As parameter increases, the effect is positive or negative.
E = Large Effect. e = Small Effect. -- = No Effect.

Collisions between medium to heavy trucks and other, smaller vehicles (principally passenger cars and light trucks and minivans) can be particularly lethal to the occupants of the smaller vehicle, principally because of the difference in weight (mass) between the two vehicles, and for head-on collisions, the high vehicle closing speeds typically involved. In total, collisions with medium to heavy trucks account for 22 percent of all passenger car and light truck/van occupant fatalities sustained in collisions with other motor vehicles (see Figure V-2). Most fatal collisions (80 percent) involving a medium to heavy truck occur on non-Interstate roads, many of which are undivided roads and have comparatively high posted speed limits. Nevertheless, on a proportional basis, the number of other vehicle occupants killed in collisions with medium to heavy trucks, is significantly higher on Interstate highways (46 percent in rural settings, 28 percent in urban settings) than on other roadway types -- an indication, in many cases, of the relatively high proportion of medium to heavy trucks in the overall traffic flow on of these roads.

Table V-2
Fatalities and Injuries in Medium to Heavy Truck Crashes - 1995

Trauma Outcome	Occupant of Other Vehicle Involved in Collision	Truck Occupant	Pedestrian, Cyclist, Other	Total
Fatalities	3,835	644	424	4,903
Injuries	83,000	30,000	6,000	119,000

Source: FARS and GES, 1995

Both the number of people killed per year in medium to heavy truck crashes, and the crash fatality rate, have decreased markedly over the past 17 years. Figure V-3 depicts the trend in the annual number of fatalities occurring in crashes involving all medium to heavy trucks and, separately, for the two principal subclasses, single units and combinations, over the past 17 years. The patterns are distinctly different, with fatalities resulting from single-unit truck crashes virtually constant while those involving combination trucks have significantly decreased.

When these fatality trends are viewed in more detail, showing separately the fatality trends for other vehicle occupants and pedestrians, distinctly different patterns can be observed, especially when considering single-unit and combination trucks separately. Proportionally, there was a greater reduction in the annualized number of truck occupants fatally injured (nearly 5 percent per year reduction in the case of combinations and 4 percent per year reduction for single-unit trucks) than there were for occupants of other vehicles involved in collisions with heavy trucks (see Figure V-4 and Figure V-5). During that time period, seat belt use among heavy truck drivers increased significantly from a low of 6 percent in 1982 to 55 percent in 1991.[1]

When the fatality trend data are normalized for exposure (VMT), the trends in fatality rate reduction are also impressive. Figure V-6 depicts the travel mileage growth pattern of medium to heavy trucks over the past 17 years. Single-unit truck travel increased at an annual rate of 3.1 percent, while the comparable growth rate for combination trucks was 3.5 percent. These data result in the fatality rate trend data for all medium to heavy trucks, and for the two principal subclasses, as shown in Figure V-7. A strongly positive decreasing trend was evident until 1992, but since then, it has leveled off and remained essentially unchanged for the last 5 years.

[1] M. Copenhaver and T. Wilkinson; *Heavy Truck Occupant Restraint Use*, U.S. DOT Report Number HS 807 752, August 1991.

FIGURE V-1

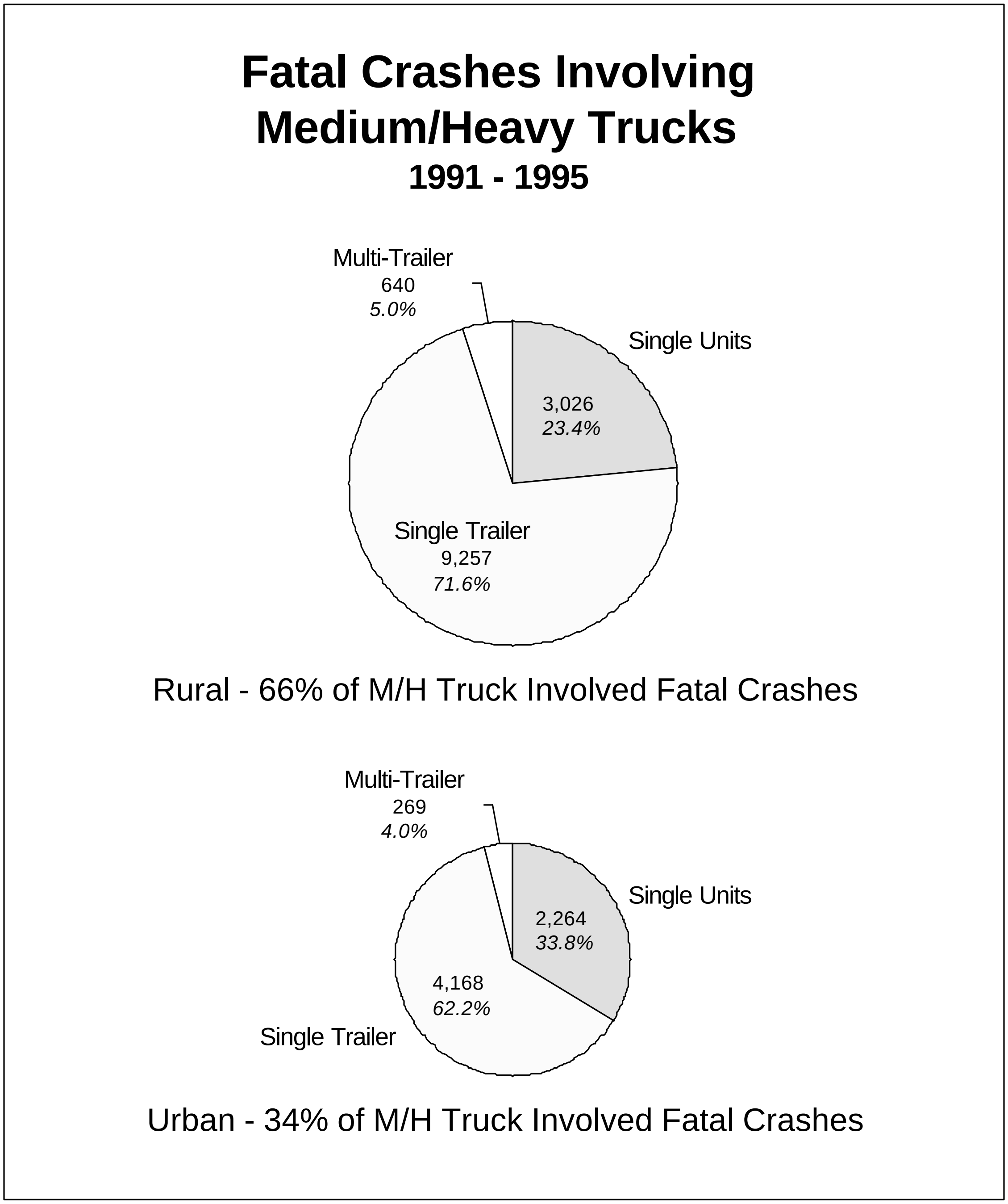
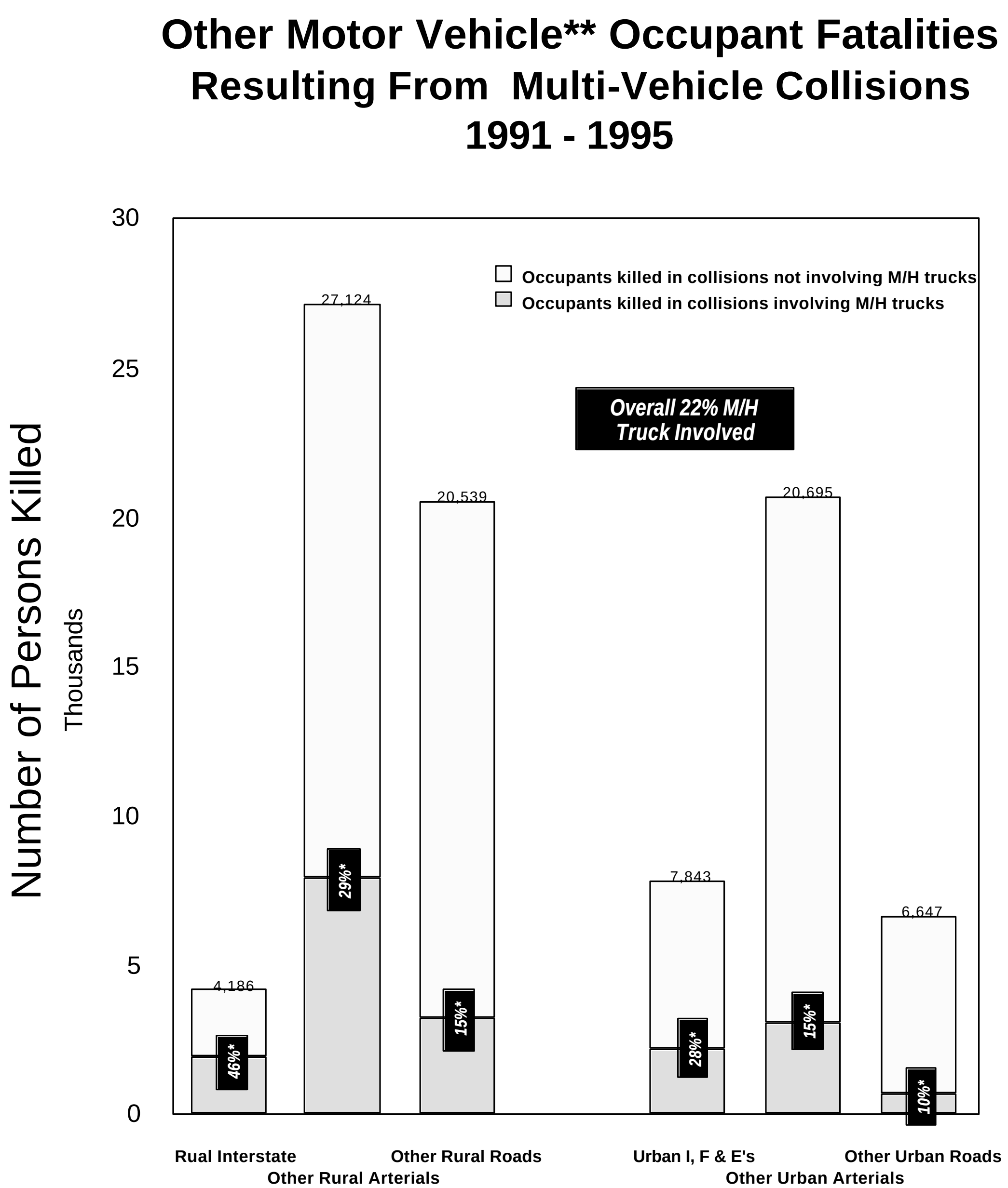

Fatal Crashes Involving
Medium/Heavy Trucks
1991 - 1995
Multi-Trailer
640
5.0%
Single Units
3,026
23.4%
Single Trailer
9,257
71.6%
Rural - 66% of M/H Truck Involved Fatal Crashes
Multi-Trailer
269
4.0%
Single Units
2,264
33.8%
4,168
62.2%
Single Trailer
Urban - 34% of M/H Truck Involved Fatal Crashes

FIGURE V-2



* Percent M/H truck involved.

** Occupants of all other motor vehicles, except M/H truck occupants.

FIGURE V-3

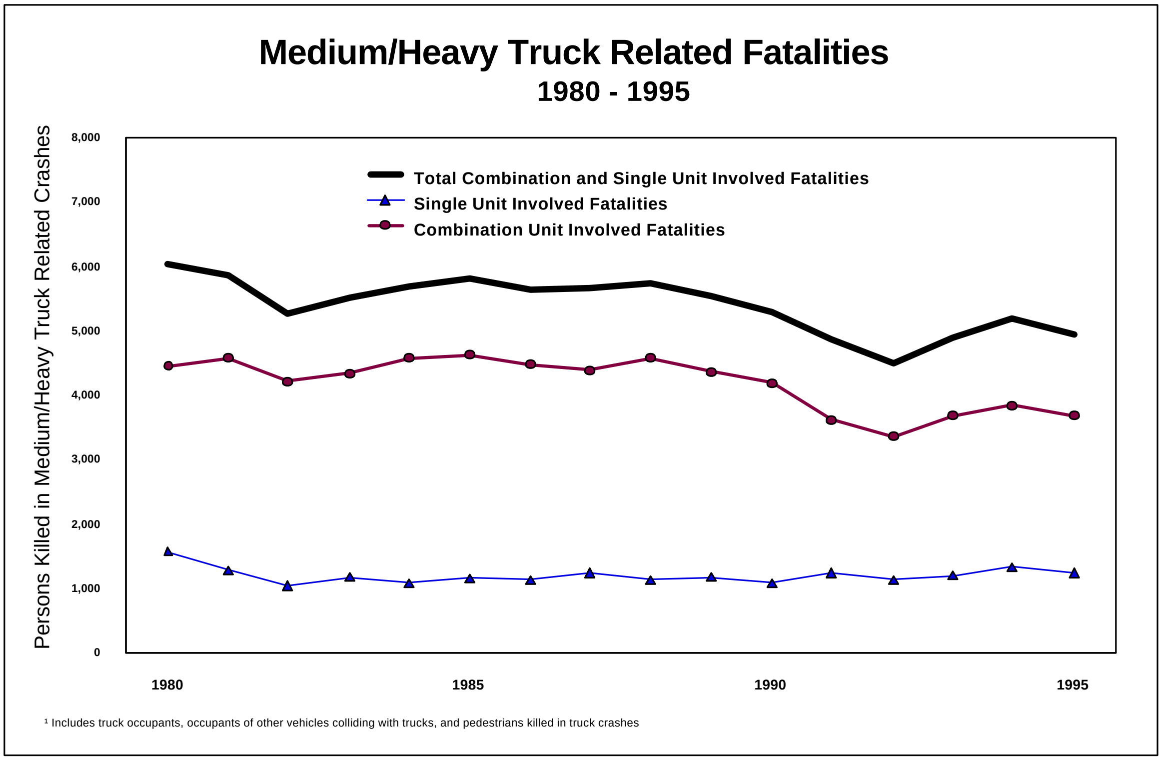


FIGURE V-4

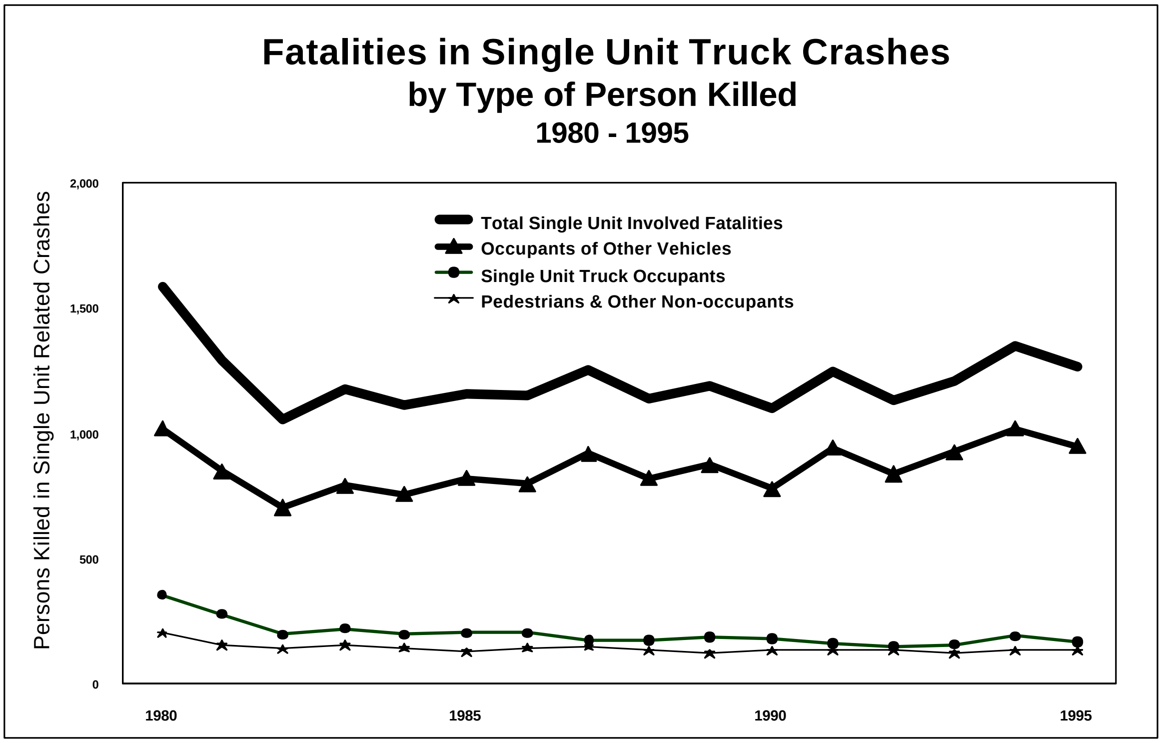


FIGURE V-5

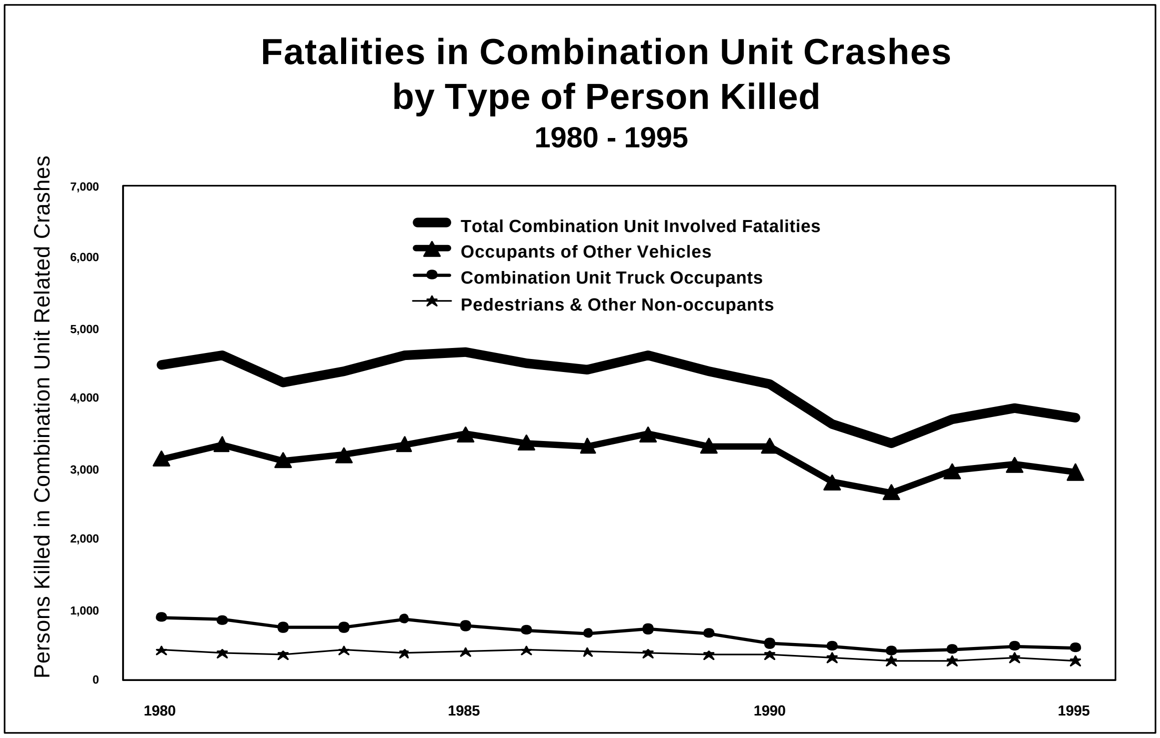
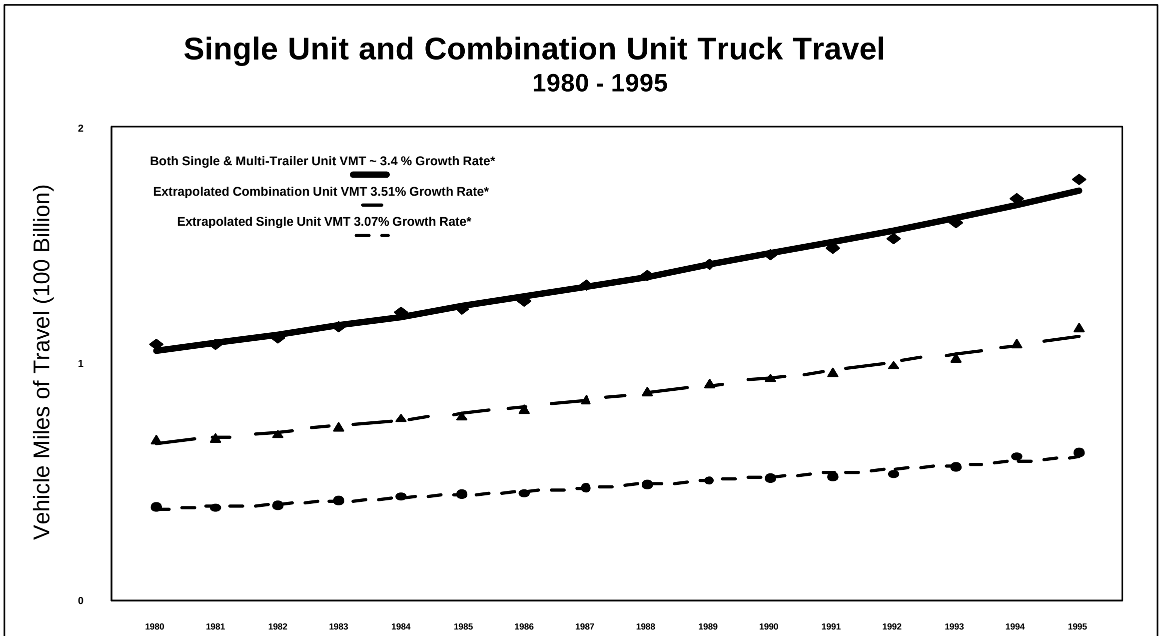
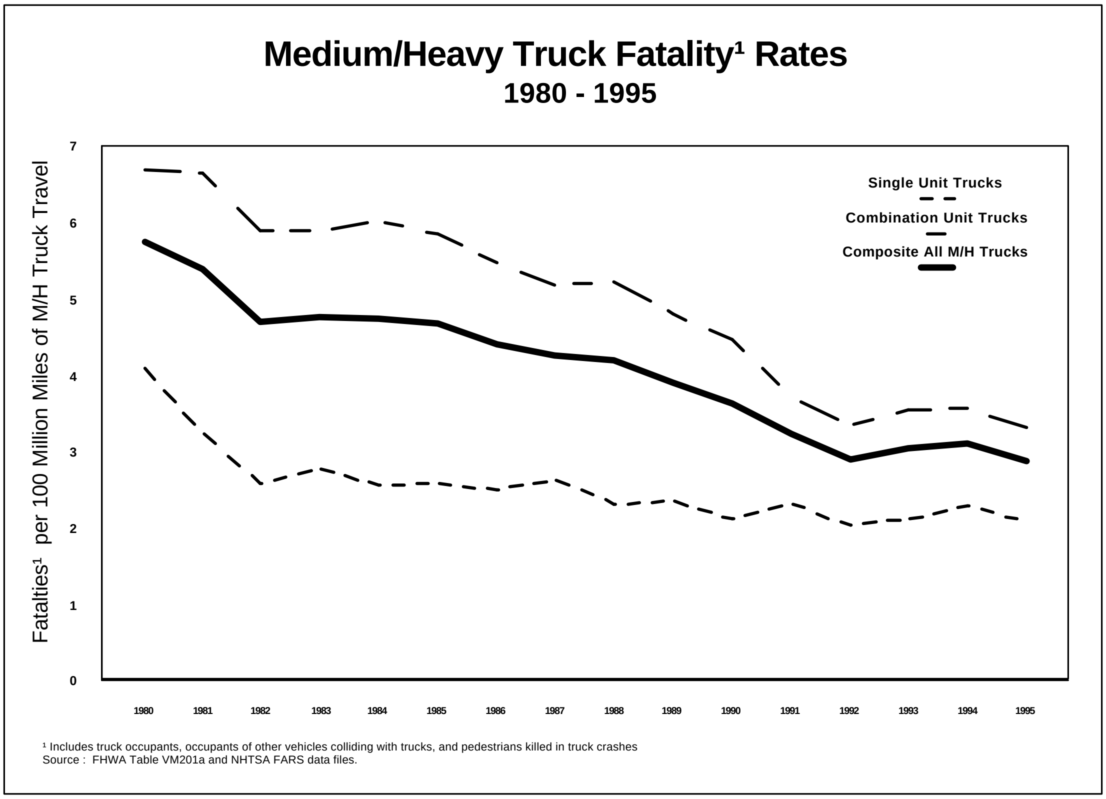


FIGURE V-6



* Growth rates based on logarithmic least squares regression on component vehicle travel for years 1980 - 1995 (1982-1995 for single unit trucks).
Source : FHWA Table VM201a.

FIGURE V-7



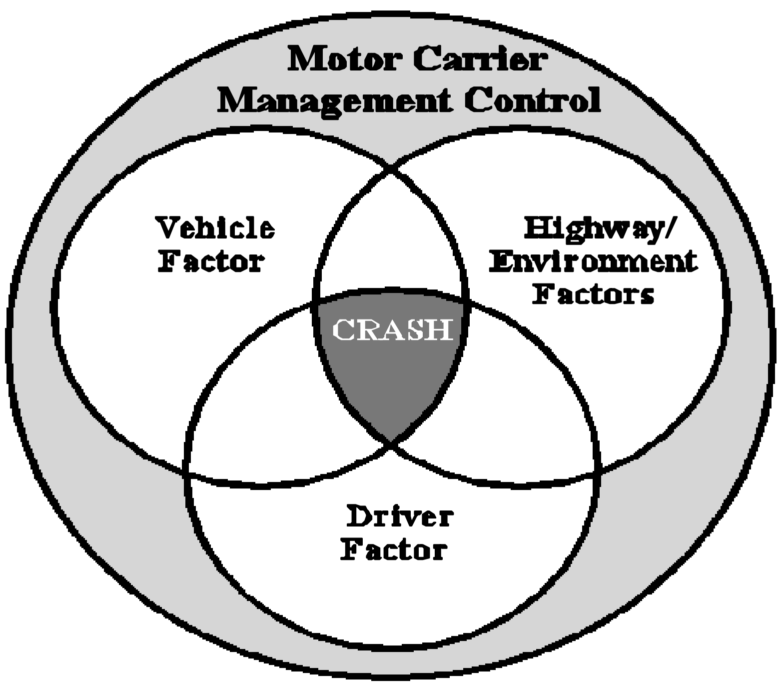
In summary, overall commercial truck safety has improved markedly in the past 17 years, a period during which the following motor carrier and vehicle safety initiatives have been implemented in the States.

* Introduction of uniform truck driver licensing and tracking of drivers' traffic violations and accident experiences under the Federal/State Commercial Driver's License Program;
* Increased Federal and State driver and vehicle inspections and motor carrier safety audits performed under the Motor Carrier Safety Assistance Program (MCSAP);
* Increased driving skill levels and safety awareness among truck drivers as a result of upgraded training received at institutions which adhere to the guidelines published by the industry-sponsored Professional Truck Driver Training Institute;
* Increased safety management effort and professionalism among motor carriers, and;
* Increased safety technology in truck designs, for example, improved seat belt designs and other truck occupant crash protection features, antilock braking systems, rear underride guards, and conspicuity treatment (reflecting tape) on trailers.

TRUCK CRASH CAUSATION AND SEVERITY FACTORS

Variables that influence the overall crash risk may be grouped into three broad categories: vehicle and equipment, driver performance, and operating environment (roadway and weather conditions). Figure V-8 illustrates the complex interrelationship of these variables as they contribute to truck crashes. Driver errors typically trigger crashes, and therefore, are overwhelmingly cited as their principal causes. Equipment considerations, which include vehicle size and weight and mechanical or operational failures, also play a role, but they are difficult to isolate. Operating environment and vehicle-related factors can diminish safety either by predisposing drivers to commit errors, or by preventing them from compensating or recovering from errors they commit. Thus, it is important to address all the contributing factors to crashes.

Figure V-8
Interrelationship of Truck Crash Factors



Source: "Heavy Truck Safety Study," U.S. DOT (HS 807 109), March 1987.

Another way of looking at the relationship of these various factors is to examine a hypothetical crash causation chain (see Figure V-9). The chain begins with predisposing conditions that, when combined with situational characteristics, create an opportunity for a crash. In other words, there is a set of factors that either predisposes or enables a crash to occur.

Figure V-9
Heavy Truck Crash Causation "Chain"

Predisposing Conditions !	Situational Characteristics !	"Trigger" Event !	"Crash" !	Outcome
! Driver - Poor Vision - Ill Trained - Poor Judgement	! Driver - Fatigued	! Driver - Inattentive, Swerves to Avoid Car Abruptly Stopping Ahead	! Jackknife/ Rollover	! Driver Killed - Total Loss/Cargo and Vehicle
! Vehicle - Low Roll Stability Threshold	! Vehicle - Maladjusted Brakes - Imbalanced Cargo ! Highway/Environment - Wet Road			
! Highway/Environment - Blind Curve - Frequent Intersections	! Management/ Operating Practices - Pushing Driver to Meet Short Delivery Time Schedule			
! Management/ Operating Practices				
! No Safety Program - "Run-To-Failure" Maintenance Policy				

Source: "Heavy Truck Safety Study," U.S. DOT (HS 807 109), March 1987.

VEHICLE AND EQUIPMENT

Vehicle factors include physical characteristics, such as the number of trailers in a combination, trailer length, and weight capacity; the dynamic performance[2] of the vehicle under various loaded conditions; and mechanical systems such as brakes and engine characteristics.

The braking capability of combination trucks is particularly important. Braking capability relates to achieving a safe stopping distance and maintaining vehicle control and stability during braking. It is influenced by a number of factors including weight and the number of wheels on the vehicle. Additionally, rollover propensity, the ability to negotiate turns and maneuver in

[2] Includes static roll stability, rearward amplification and load transfer ratio. These concepts are defined in a subsequent section.

traffic, and the ability to successfully maneuver when confronted with a potential crash threat are other performance concerns that warrant close attention. These issues are discussed in the section, “Effects of Vehicle Design on Stability, Control, and Operations.”

DRIVER PERFORMANCE

The driver is critical in preventing or initiating a crash. Driver performance factors include skill level, experience, and fatigue regardless of the type or size of truck being driven. Experienced drivers can compensate, to some extent, for strenuous driving conditions or can overcome difficulties associated with vehicles that have inferior handling and stability properties, but with increased effort. On the other hand, inexperienced drivers will be even more prone to incident involvement if the vehicles they are operating have inferior handling and stability characteristics. Further, fatigue, inattention, drug or alcohol impairment, or traveling at excessive speeds -- factors frequently cited as primary in contributing to incidents -- exacerbate these conditions.

The FHWA Office of Motor Carriers recently sponsored a study to investigate whether LCVs, with their increased length, greater weight, and greater number of trailers, could significantly increase the amount of fatigue and stress experienced by the truck driver. Data were collected from 24 experienced LCV drivers operating in a controlled test but under representative daytime driving schedules on limited access highways. After a day of orientation and training, drivers operated three types of combinations for 2 days each over a 6-day period: a single-trailer (48 foot trailer) combination, a triple-trailer combination equipped with standard A-dollies, and a triple-trailer combination equipped with self-steering, double-drawbar C-dollies.

Study findings suggest that, while the most significant contributions to driver fatigue were the characteristics of that individual driver, the number of hours since the last rest period, and the number of consecutive days of work, trailer configuration type contributed marginally to changes in driver performance. Patterns in driving performance (specifically, lane-tracking), in fatigue/physiological recovery, and subjective workload generally showed that drivers perform best when driving the single-trailer combination; next best when driving the triple-trailer combination equipped with C-dollies, and perform poorest when driving the triple-trailer combination equipped with A-dollies.

OPERATING ENVIRONMENT

Factors in the operating environment include roadway geometry, traffic congestion and adverse visibility and weather conditions. Roadway geometric features include roadway type, grades, interchanges, and intersections, as well as the interaction of trucks with other users of the highway. Longer and heavier trucks must contend with intersections, entrance and exit ramps, and highway grades with design elements that may not be suitable for all truck configurations.

The interaction of truck design features with both roadway features and visibility is accentuated as traffic volume increases. Visibility is a function of time of day as well as weather. Dawn, dusk, and night place increased operating demands on the driver to control the vehicle safely.

Crash profiles illustrated in Table V-3 show that approximately 35 percent of fatal crashes and about 26 percent of nonfatal crashes occur in visibility conditions other than normal daylight. Inclement weather, such as rain, sleet, snow, and ice, creates road conditions that challenge the stability and control of vehicles during turning and braking maneuvers.

Table V-3
Large Truck or Bus Crashes by Weather, Road Surface, And Light Conditions

Weather Conditions	Fatal	Non-Fatal		Road Surface Conditions	Fatal	Non-Fatal		Light Conditions	Fatal	Non-Fatal
No Adverse Conditions	84.6	70.1		**Dry**	79.2	72.8		**Daylight**	64.3	73.7
Rain	9.5	17.0		**Wet**	15.1	11.4		**Dark**	22.7	14.5
Sleet	0.6	5.2		**Snow/Slush**	2.4	1.4		**Dark/Lighted**	8.9	7.3
Snow	2.6	6.0		**Ice**	2.8	5.7		**Dawn**	2.7	2.4
Fog	2.0	0.2		**Sand, Oil, or Dirt**	0.1	1.5		**Dusk**	1.4	1.4

INTERACTION OF CONTRIBUTORY FACTORS

These variables, and their contribution to truck crashes, are not entirely separable. Further, crash data records do not typically delineate cause in terms of the three categories. Also, the boundary between environmental and roadway conditions is not always clear, since one may influence the other. The result is that, although several truck crash data analysis reports were reviewed (see Appendix A) to assess their validity for establishing differential crash rates for LCVs and non-LCVs, none were identified as having applicability.

Figure V-10 illustrates the driver-truck equipment performance-operating environment demands relationship. Simply stated, as the operating environment performance demands (roadway, traffic, and weather conditions) increase, driver-truck equipment performance must also increase to neutralize incident impacts. As indicated earlier, conditions of poor visibility result in increased operating demands on the truck driver. Sight distance, decision distances, and the time available for corrective or evasive action are all reduced, resulting in a need for closer control of the vehicle.

Figure V-10
Illustrative Relationship Between the Driver-truck Equipment Performance and Operating Environment Demands

Driver/Truck Equipment Performance	Operating Environment Demands: Low	Operating Environment Demands: High
High	Low Crash Probability High Performance Low Demands	Moderate Crash Probability High Performance High Demands
Low	Moderate Crash Probability Low Performance Low Demands	High Crash Probability Low Performance High Demands

Source: Heavy Truck Safety Study, DOT HS 807 109, March 1987.

CRASH SEVERITY

Crash severity is generally stated in terms of whether the crash results in property damage only, injuries, or fatalities. Four factors influence the severity of a crash involving cars and trucks: the type of collision that occurs, the relative weights of the vehicles, the change in velocity (speed) of the car, and the type of truck configuration involved in the collision. Double-trailer combinations tend to have a trailer roll over more frequently than a single-trailer combination.

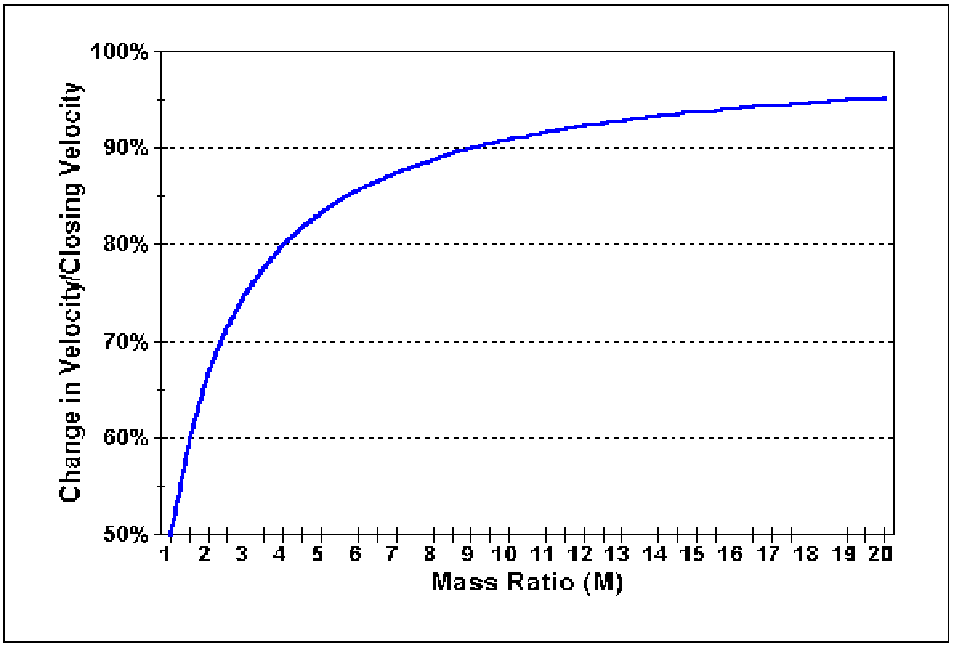
The likelihood of more severe crashes is significantly increased if truck traffic increases in operating environments with a higher risk of truck-car collisions, such as undivided highways rather than divided highways. Head-on traffic conflicts naturally create opportunities for higher closing velocities (essentially the sum of the two vehicles' speeds) that result in higher changes in velocity for the automobile involved in the conflict. Divided highways are particularly effective for truck traffic as they eliminate head-on collisions and reduce the number of all types of car-truck collisions by about a factor of two.

SPEED AND WEIGHT

When two vehicles collide, the speed at which they collide, their mass ratio, and the vehicular orientations are the primary determinants of whether a fatality results. The effect of the difference in weight between the two vehicles is large. For car-truck collisions, as compared to car-car collisions, the effect of the difference in weight between the two vehicles increases the probability that fatalities will be sustained by the occupants of the car. In such collisions, the problem is aggravated by vehicle geometric and structural stiffness mismatches. The relative closing speed at impact is the single largest predictor of the likelihood that a given crash will have a fatal outcome.

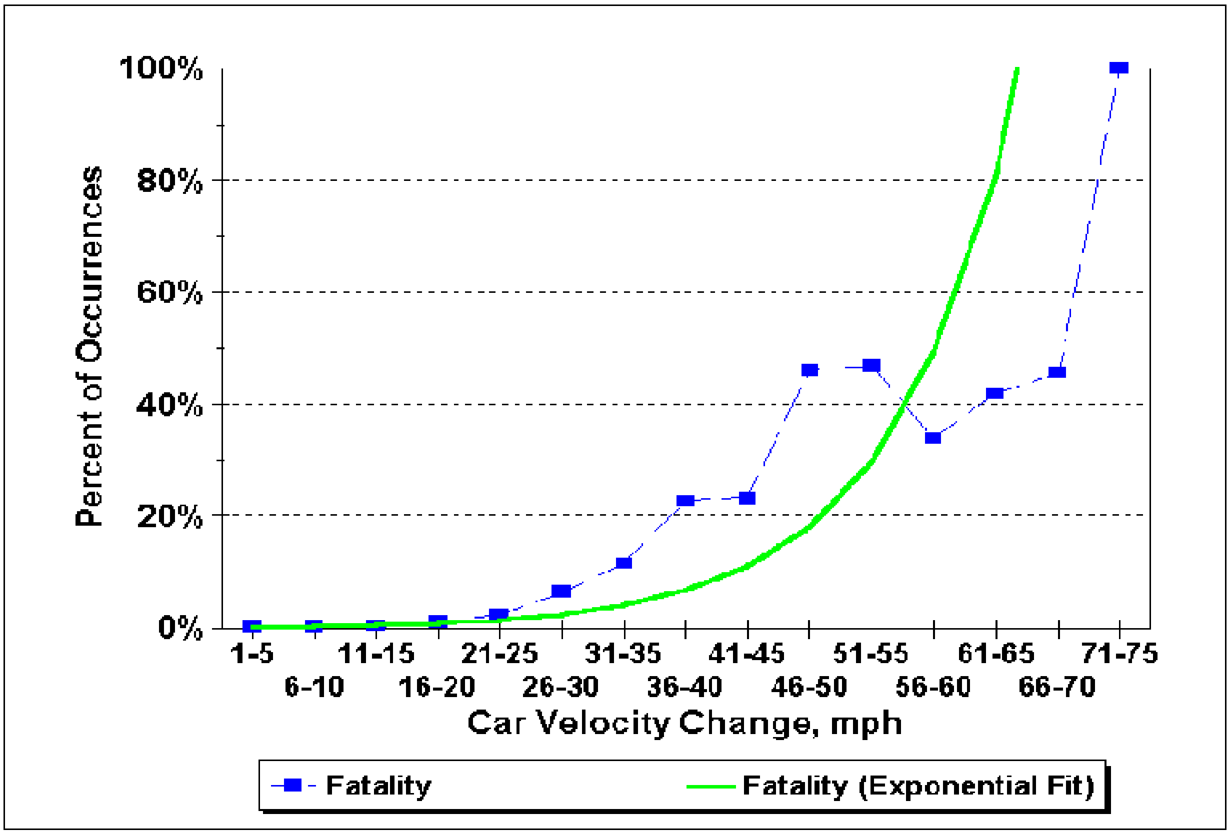
Figure V-11 illustrates the relationship between the difference in weight of two vehicles involved in collision (mass ratio) and the relative change in velocity sustained by the smaller vehicle. It assumes an impact between two vehicles of different mass traveling in opposite directions. The vertical axis represents the change in velocity of the small vehicle as a fraction of the initial closing velocity of the two vehicles. The mass ratio, simply the weight of the larger vehicle divided by the weight of the smaller, is shown along the horizontal axis. As the mass ratio increases, the change in velocity as a fraction of the closing velocity, quickly rises to exceed 90 percent at a mass ratio of nine. The graph indicates that at mass ratios around 10:1 the smaller of the two vehicles sustains virtually all the change of velocity resulting from the collision, while the larger of the two vehicles sustains little or no change. If a typical car is assumed to weigh 3,000 pounds, it can be seen that any truck weighing more than 30,000 pounds would result in ratio greater than 10:1. For a truck loaded to the current 80,000-pound limit, this ratio would be more than 25:1.

Figure V-11
Mass Ratio



The significance of the change in velocity becomes more apparent as it is related to fatality rates in car-truck crashes. The fatality data shown in Figure V-12 indicates the likelihood of a fatality as a function of the change in velocity of the vehicle. As can be seen in the figure, the data are approximated by an exponential curve that estimates 100 percent fatalities for changes of velocity that exceed approximately 65 miles per hour. These data demonstrate why, when a car and a heavy truck are involved in a head-on collision at speeds above 45 miles per hour, car occupants are highly likely to be fatally injured.

Figure V-12
Chance of Fatality as a Function of Change in Velocity



AUTO AND TRUCK DRIVER OBSERVATIONS

Twelve focus group meetings were held in 1996 to assess the perceptions, concerns, and reactions of the auto driving public and over-the-road truck drivers to operations in mixed auto and truck traffic.[3] The focus group discussions were intended to increase the understanding of safety practices, experiences, and perceptions among auto and truck drivers and to explore and assess how these groups are likely to react to possible changes in TS&W limits.

AUTO DRIVER CONCERNS

Auto drivers reported that they constantly worry about their safety when they are on the highway. They perceive the greatest threat as coming from other auto drivers -- people who are impatient, aggressive, reckless, intoxicated, or simply inattentive. They also consistently cited large commercial trucks among their top three or four highway safety concerns.

SHARING THE ROAD

Many of the focus group participants believed that truckers drive too fast, too far, and for too many hours to be safe. Truck speed and driver fatigue were among the greatest sources of auto driver concern. The focus group participants said that when they see or hear examples of a truck crash or unsafe driving by truck drivers, they begin to worry about the type of person behind the wheel. Motorists tended to attribute the truck safety problem to two sources: (1) drivers with bad attitudes, and (2) economic forces in the trucking industry that create incentives for cutting corners by inadvertently rewarding unsafe practices or placing too much pressure on drivers.

ROAD CONDITIONS

Auto drivers also cited increased traffic congestion, bad weather and the mixing of truck and auto traffic under congested or inclement conditions as factors of concern.

TS&W

Many auto drivers indicated that they feel outmatched by the size and weight of large commercial trucks. They indicated having seen or experienced dangerous and frightening interactions with large trucks on the highway, as well as news media reports of fatal truck crashes that stuck in their minds and reinforced their safety concerns.

---

[3] FHWA Focus Groups with Auto Drivers and Truck Drivers on Size and Weight Issues, Draft Final Report (Focus group findings are documented in Apogee Research, Inc., February 24, 1997).

CHANGES TO TS&W LIMITS

The vast majority of participants said they preferred the status quo regarding Federal TS&W standards or -- if changes were actually made -- a return to greater restrictions. At the same time, motorists suggested that it made little difference whether truck weights were increased or decreased because in either case they were not likely to survive a collision with a truck.

Participants said they were opposed to allowing longer trucks and trailers because they perceived such trucks to be less safe and harder to see or maneuver around. They commented that truck length is visible, and therefore, they can observe its impact on safety. With respect to LCVs, many participants said that they would not believe that doubles or triples can be operated safely. Others said doubles and triples should be used, but only under very strict limits and conditions.

Finally, the responding auto drivers doubted that they would realize any economic benefits from increased truck dimensions and felt that policy decisions would be based on narrow political or economic pressures and would undermine highway safety. Further, they indicated that they saw little evidence to suggest that current regulations were being adequately enforced, noting that they rarely saw trucks being inspected or pulled over for speeding.

TRUCK DRIVER CONCERNS

The truck drivers who participated in the focus groups generally felt that their jobs were potentially dangerous and required that they be constantly vigilant regarding external threats to their safety.

SHARING THE ROAD

The truck drivers cited automobile drivers as their biggest complaint. They indicated that, from their perspective, auto drivers are increasingly unpredictable. Further, increased traffic and traffic congestion have made potential safety problems worse, particularly around urban areas. The truck drivers indicated that better driver education -- for automobile drivers -- might improve the situation.

ROAD CONDITIONS

Truck drivers felt that traffic congestion is getting worse. They also perceived that the highways are less able to accommodate their larger, heavier trucks, which creates more potential hazards. Road design, highway conditions, and construction practices were seen as challenging maneuverability and safe operations.

TRUCK DRIVER EXPERIENCE AND TRAINING

Truck drivers place a high premium on skill and experience. This makes veteran truck drivers leery of new drivers whom they feel are being rushed through training that they -- experienced drivers -- perceive to be inadequate because it focuses on preparing them to obtain a commercial driver's license and not necessarily to be a safer driver.

TS&W

Weight was considered a key variable in truck safety; it was seen as determining a driver's ability to maintain control under different conditions. However, according to the driver, a heavier truck is not necessarily a less safe truck. Trailers were reported as being too long for many city streets, and even for some ramps and access roads along Interstate highways.

Truck drivers felt that experienced, responsible drivers are safely operating heavy trucks, but safe operation may be threatened by shippers, dispatchers, and companies that tend not to allow sufficient time for deliveries. Economics was seen as the most fundamental determinant of truck safety, because it is such a dominant factor in influencing driving conditions -- truck weight, operating speed, and driver fatigue.

CHANGES TO CURRENT TS&W LIMITS

The drivers said, with considerable pride, that they could operate “anything” and confidently indicated that they could handle any increase in TS&W that might occur. However, they were skeptical about the need for or desirability of allowing longer or heavier trucks on the highways. They said that maintaining safety would require changes in highway conditions, training, equipment, and economic incentives. Truck drivers were skeptical that the necessary changes would be implemented.

Truck drivers generally opposed changing the TS&W standards. The majority preferred to maintain the status quo or return to a more restrictive set of standards, particularly if the latter would make the rules more uniform from State to State. Keeping up with the different, and even contradictory, rules was reported as a time-consuming distraction. Further, nonuniformity was reported as adding to stress, fatigue, and costs. Truck drivers also reported that, to ensure highway safety, special restrictions should be required in LCV operations.

If the regulations were made less restrictive, the drivers said, more skill, experience, effort, and time would be required to maintain safety on the highway. The drivers were doubtful that these requirements would be met, given the problems they had previously cited.

EFFECTS OF VEHICLE DESIGN ON STABILITY, CONTROL AND OPERATION

Differing TS&W policies can affect the safety and traffic operations characteristics of heavy trucks as they lead carriers to choose particular vehicle design features and configurations for their operations. The vehicle dynamic properties of rollover, maneuverability, and the ability to avoid unanticipated crash threats are directly affected by truck (especially for long and heavy trucks) weight, dimensions (including the height of the loaded truck's center of gravity, number of axles, and number of articulation points in combination trucks. The relevant design features and specifications include:

- Overall vehicle length and wheelbase;
- Vehicle track width;
- Overall vehicle weight;
- Individual axle weights;
- Number of axles and tires on vehicle;
- Number of units in a combination vehicle; and
- Number of articulation points in a combination vehicle.

Important vehicle equipment specifications also include the types of tires and braking and suspension systems.

In some cases, these vehicle design features and equipment limit vehicle performance in traffic, which reduces the driver's ability to successfully execute abrupt or extreme maneuvers. Unless other compensatory changes in driver performance and operating environment demands are made to counteract the effects of vehicle performance differences, crash likelihoods and traffic disruption effects increase somewhat.

Rollovers account for 8 to 12 percent of all combination truck crashes, but are involved in approximately 60 percent of crashes fatal to heavy truck occupants. They greatly disrupt traffic when they occur in urban environments, particularly when hazardous materials are involved. Rollovers can be reduced by making vehicles more roll stable through design changes such as lower deck heights, more axles, and stiffer suspensions. Another solution would be for drivers never to exceed posted or reasonable speeds when traversing curves or exit ramps. There are three performance measures that have evolved as being the principal indicators of crash risk due to vehicle design changes: static roll stability, rearward amplification, and load transfer ratio. All three describe aspects of a vehicle's basic or inherent propensity to roll over when turns or out-of-the-ordinary crash avoidance maneuvers are attempted.

BRAKING PERFORMANCE

Braking performance is a general concern that applies to all trucks and is not particularly influenced by changes in TS&Ws, if the requisite number of axles and brakes are added as the vehicle's weight increases and all the vehicle's brakes are well-maintained. Antilock braking systems, now required on all trucks, will greatly enhance their braking performance and will be especially beneficial to multitrailer combinations.

The most straightforward metric of brake system performance is the distance required to stop the vehicle when fully loaded. Obviously, shorter distances are better in this regard. However, brakes must also be able to absorb and dissipate large amounts of kinetic energy when a fully loaded truck descends a grade. Also, trucks need to be able to stop in a stable manner, without jack knifing or otherwise losing directional control due to wheels locking and skidding. Studies have indicated that brake system performance plays a contributing role in approximately one-third of all medium-to-heavy truck crashes.[4]

The ability to stop in short distances mostly depends on the size and number of brakes on the vehicle, their adjustment and state of maintenance, and tire properties. If the vehicle's brakes are adequately sized -- and virtually all are as a result of Federal regulatory requirements -- they are capable of generating enough force to lock most wheels on the vehicle when it is fully loaded. However, inadequately maintained or maladjusted brakes cannot generate needed braking power, which leads to longer stopping distances. Improper brake balance can cause downhill runaways and braking instability. Furthermore, adding more load to a given vehicle without adding axles and brakes degrades stopping performance.

HIGH-SPEED OFFTRACKING

When a combination vehicle negotiates a sweeping (long radius of curvature) high-speed curve, as it would at some interchanges between freeways, the rearmost trailer axle can track outside the path of the tractor steering axle. For most truck configurations analyzed, this offtracking is 1 foot or less at 55 miles per hour. This tendency is reduced on superelevated curves. Conceivably, if the trailer wheels were to strike any outside curb during negotiation of the curve, a rollover could occur, but this performance attribute has not been linked to any appreciable number of truck crashes. High-speed offtracking is related to a vehicle's rearward amplification tendencies and is indirectly addressed when rearward amplification is addressed.

TRAFFIC OPERATIONS EFFECTS

There are other measures of a vehicle's ability to negotiate turns or otherwise "fit" within the dimensions of the existing highway system. The principle metric is low-speed offtracking, however, there is little, if any, link between this performance attribute and the likelihood of serious crashes (fatal or injury-producing), although excessive offtracking can disrupt traffic flow and damage infrastructure. This latter impact is discussed in Chapter 6, Highway Infrastructure.

[4] "Improved Brake Systems for Commercial Vehicles," U.S. DOT (HS 807 706), April 1991.

Acceleration performance determines a truck's basic ability to blend well with other vehicles sharing the roadway with it; for example, hill climbing and acceleration ability, time to pass or be passed on a two lane road, merging at interchanges, which can be incrementally degraded as trucks increase in size or weight and, therefore, need to be addressed as well when considering the ability of a given segment of roadway to safely accommodate longer and heavier trucks.

LOW-SPEED OFFTRACKING

When a combination vehicle makes a low-speed turn -- for example at a 90-degree intersection -- the wheels of the rearmost trailer axle follow a path several feet inboard of the path of the steering axle. If excessive, this phenomenon (low-speed offtracking) may force the driver, when executing a turn, to swing wide into adjacent lanes to avoid climbing inside curbs or striking curbside objects. Excessive offtracking can disrupt traffic operations or result in shoulder or inside curb damage at intersections and interchange ramp terminals that are designed like intersections if they are heavily used by trucks.

Low-speed offtracking is affected primarily by the distance from the tractor kingpin to the center of the trailer's rear axle or axle group. For a semitrailer, this distance is its effective wheelbase. In the case of a multitrailer combination, the effective wheelbases of all the trailers in the combination, along with the tracking characteristics of the converter dollies, affect offtracking. In general, longer wheelbases worsen low-speed offtracking. Chapter 6 provides data on the extent of offtracking for a variety of truck configurations and trailer lengths.

Standard STAA double (two 28-foot trailers) and triple (three 28-foot trailers) combinations offtrack less than the standard tractor and 53-foot semitrailer combination, as they have more articulation points in the vehicle combination and use trailers with shorter wheelbases. Low-speed offtracking is a readily measured and/or calculated metric.

VEHICLE ACCELERATION AND SPEED MAINTENANCE

As a vehicle's weight increases, its ability to accelerate quickly and to climb hills at prevailing traffic speeds is degraded, unless larger engines or different gearing arrangements are used. Poor acceleration is a concern when it results in large speed differentials between vehicles in traffic as crash risks increase significantly with increasing speed differential. Table V-4 indicates that crash involvement may be from 15 to 16 times more likely at a speed differential of 20 miles per hour.

Table V-4
Speed Differentials and Crash Involvement

Speed Differential (mph)	Crash Involvement	Involvement Ratio (Related to 0 Speed Differential)
0	247	1.00
5	481	1.95
10	913	3.70
15	2,193	8.88
20	3,825	15.49

Source: H. Douglas Robertson; David L. Harkey; and Scott E. Davis; Analysis Group, Inc.; "Safety Criteria for Longer Combination Vehicles," August 1987.

ON STEEP GRADES

On routes with steep grades frequently traveled by trucks, special truck climbing lanes have been built. Otherwise, trucks should be able to maintain reasonable grade climbing performance. In the past, hill climbing performance has been addressed by requiring larger trucks to be equipped with higher horsepower engines. However, this can be counterproductive, since larger engines tend to consume more fuel and emit air pollutants. While in some cases larger engines may be necessary to maintain grade climbing performance, a more easily enforced approach is to specify minimum acceptable speeds on grades and minimum acceptable lengths of time to accelerate from a stop to 50 miles per hour or to accelerate from 30 to 50 miles per hour.

If single drive axle tractors are used in multitrailer combinations the tractor might not be able to generate enough tractive effort to pull the vehicle up the hill under slippery road conditions. In these cases, either tandem-axle tractors or tractors equipped with automatic traction control could be used.

NON-SIGNALIZED INTERSECTIONS

Heavier vehicles entering traffic on two-lane roads from non-signalized intersections could require more time to reach operating speed. Also, longer vehicles crossing non-signalized intersections from a stopped position on a minor road could increase by up to 10 percent the sight distance required by traffic on the major road. If sight distances at the intersection are obstructed, approaching vehicles might have to decelerate abruptly, which could cause a crash or disrupt traffic flow.

The degree to which larger or heavier trucks perform worse than others, which is of particular concern in cases where frequent truck-car conflicts can be anticipated, depends on their comparative acceleration performance characteristics. If equipped with appropriate powertrains that ensure adequate acceleration performance, or if routes were screened for suitability, these concerns would be minimized, regardless of the vehicle size or configuration.

AERODYNAMIC EFFECTS

Truck-generated splash and spray is sensitive to vehicle aerodynamics. Another aerodynamic effect is the buffeting of adjacent vehicles from air turbulence. Air turbulence around trucks is not increased with truck length or weight. Rather, the front of the truck and gaps between the tractor and the semitrailer(s) it tows can be the source of a transient disturbance to adjacent vehicles, especially if they are operating in substantial crosswinds. Double-trailer combinations have two of these gaps, while triple-trailer combinations have three.

Efforts to improve truck aerodynamics are continual, since the fuel economy benefits that result are substantial. Both buffeting and splash and spray effects will be reduced as market-driven product development proceeds.

SUMMARY

Notwithstanding driver, roadway, and weather effects, only in cases of component failure does vehicle performance directly cause a crash to occur. Importantly however, marginal or inferior stability and control performance can make it difficult, if not impossible for a driver to recover from an error, or avoid an unforseen conflict. Multitrailer combinations without compensating design features have inferior performance capabilities compared to single-trailer combinations and these differences, especially if frequently challenged in traffic conflict situations, result in incrementally higher crash likelihoods.

PERFORMANCE-BASED APPROACH TO TS&W REGULATION

Some countries allow more productive trucks under a performance-based approach to ensure that these trucks would, under certain restrictions, enhance highway safety, that is, decrease the likelihood of a crash. The ultimate approach to TS&W regulation would be based on how a vehicle performs, that is, its roll stability when turning or making an evasive maneuver, the amount of wear it imposes on pavements and bridges, and how it fits on the highway system relative to intersections and sharp curves. This is in contrast to regulation of the physical characteristics (such as weight and dimension specifications -- TS&W limits) with which a vehicle must comply before it may be operated. For example, TS&W regulations could require that a vehicle: (1) deflect a pavement no more than a certain accumulated amount, (2) cause a bridge to be stressed no more than a certain level, (3) offtrack no more than a certain distance, or (4) have a tendency to roll over no greater than a given level.

For ease of regulatory compliance and enforcement, traditionally, TS&W limits have been set so that a vehicle complying with these limits is determined to perform within acceptable limits. Historically, in the United States, vehicle performance has been of concern relative to pavement and bridge consumption and low-speed offtracking. However, other concerns have arisen regarding: (1) acceleration ability for climbing steep grades, entering freeway traffic, and clearing intersections; (2) the time required to pass or be passed by other vehicles, which is a function of vehicle speeds and overall lengths; and (3) vehicle stability when making tight turns such as on freeway interchange ramps or when making high-speed evasive maneuvers. Current Federal TS&W limits have not been based on these latter performance concerns, although they have been considered in the evaluation of potential changes to the current limits such as for this Study.

Experience under the current regime of Federal TS&W law and regulation has shown that trucks, though being in compliance with regulatory limits, perform outside intended standards, especially for bridge stress levels. This results from the simple specification of the current regulations, which nevertheless, provide for easier compliance and enforcement. Several countries employ various forms of a performance-based approach to TS&W regulation, and among these countries a broad range of limits are specified. A recent study[5] examined TS&W regulations in approximately 30 industrialized countries and found that the greatest disparity among countries was in the gross weights allowed, which ranged from 61,700 pounds in Switzerland to 110,200 pounds in Norway for a 5-axle semitrailer combination. Further, authorities use different performance criteria to regulate vehicles, such as, dynamic stability, turning abilities, and ability to maintain speed. Table V-5 describes various performance measures, most of which are in effect in various countries.

ALTERNATIVE APPROACHES

There are two basic methods for implementing performance based regulations: (1) vehicle type certification with the certification shown for enforcement purposes by a placard on the vehicle or vehicle unit or by a permit in the power unit, and (2) the “envelope vehicle” approach with weight and dimension specifications depending on the type of truck configuration: single-unit truck, single-trailer combination, and multitrailer combination (see Exhibit V-20). The remaining performance-based approach discussion primarily focuses on performance criteria that measure a vehicle’s tendency to avoid rolling over, that is, its stability when turning (especially in tight turns at low speeds) and making evasive maneuvers at high speeds.

[5]"Applicability of Performance-Based Standards to Truck Size and Weight Regulation in the United States,” James York and Tom Maze, in *Road Transport Technology -- 4: Proceedings of the Fourth International Symposium on Heavy Vehicle Weights and Dimensions, June 25-29, 1995*. Ed. Christopher B. Winkler. pp. 37-142.

Table V-5
Example Safety Performance Measures

Performance Measure	Country	Description
Rollover Threshold	**Canada New Zealand**	**The lateral acceleration at which a vehicle rolls over when it is driven in a steady circular turn. It is customarily measured in "g", the lateral acceleration relative to gravitational acceleration (32.2 ft/sec^2).**
High-Speed Offtracking	**Canada New Zealand**	**The distance between the path of the last axle in a configuration and the steering axle (the "lateral offset" to the outside) in a steady turn at high speed.**
Rearward Amplification	**None**	**The ratio of the peak lateral acceleration of the rear trailer of a multiple trailer combination vehicle to the peak lateral acceleration of the power unit in a rapid steering maneuver that results in a lateral offset movement of the vehicle, such as might be required to avoid an obstacle in its path.**
Dynamic Rollover Stability	**Canada New Zealand**	**An objective safety outcome of rearward amplification, describing how close a truck or unit of a combination, usually the last trailer, comes to rolling over in a rapid steering maneuver.**
Transient High-Speed Offtracking	**Canada New Zealand**	**A second objective safety outcome of rearward amplification, describing the extent by which the rear axle of a combination tracks outside the path of the steering axle of the tractor in a rapid steering maneuver.**
Low-Speed Offtracking	**Canada New Zealand**	**The distance between the path of the last axle in a configuration and the steering axle in a low-speed turn. The last axle typically tracks inboard of the steering axle.**
Turning Circle	**European Union**	**Performance is measured by tracing the path of the furthest outward projection (that is, tractor front bumper) of a vehicle and the path of the furthest inward projection (that is, trailer rear corner).**
Friction Demand (In Tight Turn)	**Canada**	**The minimum level of pavement friction on which a vehicle can negotiate an intersection turn without under-steering excessively.**
Braking Efficiency	**Canada**	**A measure of the amount of tire/pavement friction used, compared to the amount available, before the wheels lock up. Another measure is the ability to stop in a controlled manner within a certain distance (stopping performance).**
Gradeability Startability and Acceleration	**Finland British Columbia**	**The ability of a truck to accelerate through an intersection or a rail crossing and the ability of a truck to maintain speed on a grade are related to the power of the engine, and the characteristics, particularly the weight, of the truck.**

Regarding the implementation of the vehicle type certification approach in particular, the general consensus of opinion expressed in interviews of State officials during this Study is that any assessment of the institutional feasibility of a performance-based approach has to be tentative unless or until it is decided what aspects of performance are included, how these attributes can be measured, and how truck performance can be tested by those responsible for TS&W regulation. Canadian and New Zealand experiences with these approaches follow.

CANADA

The Canadian experience with performance-based standards for trucks and truck combinations evolved out of a study conducted by the Road Transport Association of Canada (RTAC) in the early 1980's. The RTAC process studied many of the performance measures outlined in Table V-6 and based on those analyses established truck configurations that were known to meet the following criteria: (1) interact acceptably with the highway infrastructure; (2) have higher safety performance properties than existing configurations; and (3) increase productivity for industry.

However, Canada did not specify its regulations in performance terms. After evaluating the vehicle stability and control (VS&C) performance, it determined the vehicle weights and dimensions required to ensure that performance standards would be met for each of several truck configurations. This is the “envelope vehicle” approach. It differs from the U.S. Federal approach in two ways: (1) VS&C performance was explicitly considered along with pavement and bridge wear considerations, and (2) weights and dimensions are specified by truck configuration type.

A list of the acceptable configurations was developed to achieve a degree of uniformity in size and weight limits among the Provinces. Benefits evolving from the application of the RTAC approach included expansion in the use of the tridem-axle group in Canada, and improvements in stability and control of larger combinations through the use of B-train doubles with additional weight. In 1989 the Provinces and Territories agreed to implement recommendations from the RTAC Study through a Memorandum of Understanding on Vehicle Weights and Dimensions.

Table V-6
Pros and Cons of Two Performance Based (PB) Approaches to TS&W Regulation

Vehicle Type Certification	**Pros**	**Gives truck manufacturers and motor carriers greater flexibility to create more productive trucks. This is particularly useful for freeway/turnpike operations or special hauling arrangements of natural resources in remote areas.**
		Insures that vehicle performance requirements are met irrespective of changing truck technology, which otherwise can have unanticipated negative impacts in the future.
		A permit provides a means for collecting fees for any additional highway cost responsibility occasioned by larger, heavier trucks.
		Can screen out undesirable truck configurations.
	Cons	**Initial certification of type compliance is an involved process, but once done, it is valid for all trucks of that type for the jurisdiction(s) accepting the certification.**
		Compliance with and enforcement of the performance-based approach are more cumbersome and potentially more costly depending on the operating and equipment specifications of the certification/permit.
		Capability to certify vehicle type compliance is presently minimal and time will be required for the needed licensed professional capability to become available.
		Being a new approach, it would require putting new organizational structure and procedures in place.
Envelope Vehicle	**Pros**	**Simple compliance, administrative, and enforcement procedures.**
		Easily implemented as compliance and enforcement mechanisms are largely in place.
	Cons	**The accommodation of innovative truck designs would often require legislative action.**
		Future truck designs meeting envelope vehicle parameters could perform worse than the standards that resulted in the "envelope" specifications.
		Current TS&W regulations are largely independent of truck configuration type, which adds a significant dimension to TS&W regulation.
		Requires performance assessments by public agencies.

Sources: Interviews of State Officials conducted during the study.
FHWA sponsored "1995 Truck Size and Weight Performance-Based Workshop," Ann Arbor, Michigan.
"Truck Weight Limits: Issues and Options," Special Report 225, TRB, National Research Council, Washington, D.C., 1990.

NEW ZEALAND[6]

The New Zealand performance-based approach (vehicle type certification) requires evidence of a productivity improvement and no reduction in safety levels from the existing condition. The regulations are guided by performance and service principles established by the Land Transport Safety Authority (LTSA), a Crown entity that is controlled by a Board of Directors selected from industry. The LTSA serves as advisor to the government on land transport safety issues. Proof of no reduction in safety levels is the demonstration of vehicle dynamic performance using computer simulation models.

Among the restrictive conditions to ensure that safety is not compromised are: (1) the design of the vehicles must be such that the simulated loading conditions cannot be exceeded, assuming the highest density product for which the approval is valid (has the effect of being limited to enclosed trailers, such as van and tank trailers); (2) no tolerances shall be applied to the vehicle weights prescribed (design capacity must not exceed the approved weight for the approved commodity); (3) maximum speed capability shall be controlled to 90 kilometers per hour; (4) an approved tachograph or electronic speed-time recording device shall be fitted and used at all times and the output made available to any enforcement officer on request; and (5) the stability levels specified shall be achieved by every unit of the combination.

An 88,000-pound, A-train double-trailer combination policy for milk trucks was the first regulation developed under the process, and any A-train combination that meets the performance standards under all loading conditions can be considered for approval. This approval required compliance with three stability performance measures: (1) static roll threshold of 0.45 g's or greater; (2) dynamic load transfer ratio of 0.6 or less; and (3) high speed transient offtracking of 0.5 meters or less.

This process has resulted in significant costs and related difficulties for industry. It was found that only one organization existed in New Zealand with the capability of conducting the simulation testing. Additional difficulty arose from the lack of data needed for testing vehicles and components. Consequently, the performance standards were revised through negotiations between the LTSA and industry. Since only twenty vehicles have been qualified and are operating under the A-train double-trailer policy, the policy is considered a limited success.

---

[6] "Regulating Heavy Vehicle Safety in New Zealand Using Performance Standards," John Edgar, LTSA, New Zealand. In *Road Transport Technology -- 4: Proceedings of the Fourth International Symposium on Heavy Vehicle Weights and Dimensions*, June 25-29, 1995. Ed. Christopher B. Winkler. pp. 115-119.

REFERENCES

Baas, Peter H.; White, David M. 1989. "Safety Improvements for Increased Weights and Dimensions in New Zealand," *Proceedings of Second International Symposium on Heavy Vehicle Weights and Dimensions,* Kelowna, British Columbia.

Billing, J.R. 1995. "Implementation of Vehicle Weight and Dimension Regulations." In *Road Transport Technology - 4, Proceedings of the Fourth International Symposium on Heavy Vehicle Weights and Dimensions.* Ann Arbor, Michigan, June 25-29, 1995. pp. 107-114.

Billing, J.R. 1992. "A Discussion of Performance Standards for Configurations of Heavy Trucks," *Heavy Vehicles and Roads: Technology, Safety and Policy*. Third International Symposium on Heavy Vehicle Weights and Dimensions. Cambridge U.K. Eds. D. Cebon & C.G.B. Mitchell. Thomas Telford Services Ltd, London. pp. 278-283.

Canroad Transportation Research Corporation. 1986. *Vehicle Weights and Dimension Study: Technical Steering Committee Report,* RTAC, Ottawa, Ontario, Canada.

Edgar, John. 1995. "Regulating Heavy Vehicle Safety in New Zealand Using Performance Standards," In *Road Transport Technology - 4, Proceedings of the Fourth International Symposium on Heavy Vehicle Weights and Dimensions.* Ann Arbor, Michigan, June 25-29, 1995. pp. 115-119.

El-Gindy, M. 1992. "The Use of Heavy Vehicle Performance Measures for Design and Regulation," *Transportation Systems - 1992,* DSC-Volume 44, The American Society of Mechanical Engineers, New York, N.Y.

TRB. 1990a. *Truck Weight Limits: Issues and Options,* Special Report 225, National Research Council, Washington, D.C.

TRB. 1990b. *New Trucks For Greater Productivity and Less Road Wear: An Evaluation of the Turner Proposal,* Special Report 227, National Research Council, Washington, D.C.

UMTRI. 1995. *Road Transport Technology--4, Proceedings of the Fourth International Symposium on Heavy Vehicle Weights and Dimensions*. Edited by Christopher B. Winkler.
Winkler, C.B.; Fancher, P.S.; Bareket, Z.; Bogard, S.; Johnson, G.; Karamihas, S.; and Mink, C. 1992. *Heavy Vehicle Size and Weight -- Test Procedures for Minimum Safety Performance Standards,* Report Number DOT HS 807 855. U.S. DOT, NHTSA, Washington, D.C.

APPENDIX A

SUMMARY OF TRUCK CRASH RATE ESTIMATES FROM SELECTED STUDIES

Table V-7 lists crash rate estimates compiled through the review of seven sources (listed in Table V-8). As can be seen in the Table, a variety of quantities are presented depending on the specific source. One might compare the crash rates of different truck configurations within a single study, however, there is no assurance that a different study with a different population would agree with the findings of another study. No data set presently available contains both crash and exposure information on all of these aspects of LCVs or non-LCVs in sufficient detail to fully address questions as to the differences in their comparative crash involvement histories.

Table V-7
Crash Rates from Past Studies
(Per MVMT)

<table>
<tr><th rowspan="2">Truck Configuration</th><th colspan="7">Source</th></tr>
<tr><th>A</th><th>B</th><th>C</th><th>D</th><th>E</th><th>F</th><th>G</th></tr>
<tr><td>Single-Unit</td><td></td><td></td><td>0.369</td><td></td><td>Fatal 0.009
All 0.86</td><td></td><td></td></tr>
<tr><td>Semitrailer</td><td>Local 1.51
Intercity 0.812</td><td>All 6.79
Casualty 1.51</td><td>0.486</td><td>Interstate 3.83
Other Hwys 28.45
Locals 15.65</td><td>Fatal 0.035
All 1.38</td><td>Fatal 0.0244</td><td>Fatal 0.0298</td></tr>
<tr><td>Truck-Trailer</td><td rowspan="4">Local 0.981
Intercity 0.833</td><td rowspan="2">All 5.69
Casualty 1.61</td><td>0.584</td><td rowspan="4">Interstate 3.52
Other Hwys 18.8
Locals 9.96</td><td></td><td></td><td></td></tr>
<tr><td>STAA Double</td><td>0.458</td><td rowspan="3">Fatal 0.043
All 1.39</td><td rowspan="3">Fatal 0.0208</td><td rowspan="2">Fatal 0.0346</td></tr>
<tr><td>RMD</td><td></td><td></td></tr>
<tr><td>Turnpike Double</td><td></td><td></td><td></td></tr>
</table>

Table V-8
Sources For Information in Table V-7

A	**"Comparison of Accident Characteristics and Rates for Combination Vehicles with One or Two Trailers," Thipatai Chirachavala and James O'Day, UMTRI Report UM-HSRI-81-41, August 1981.**
B	**"Differential Truck Accident Rates for Michigan," Richard W. Lyles; Kenneth L. Campbell; Daniel F. Blower, and Polichronis Stamatiadis, Transportation Research Record 1322.**
C	**"Analysis of Accident Rates of Heavy-Duty Vehicles," Kenneth L. Campbell, Daniel F. Blower; R. Guy Gattis, and Arthur C. Wolfe, UMTRI Report, April 1988.**
D	**"Comparison of Accident Rates for Two Truck Configurations," Paul P. Jovanis; Hsin-Li Chang; and Ibrahim Zabaneh, Transportation Research Record 1249.**
E	**"Truck Accidents by Classification," V.D. Graf and K. Arculeta, CALTRANS, FHWA/CA/TE-85.**
F	**"Larger Dimensioned Vehicle Study, Final Report" FHWA, September 1993.**
G	**"Comparison of California Accident Rates for Single and Double Tractor-Trailer Combination Trucks," C.S. Yoo; Martin L. Reiss; and Hugh W McGee; BioTechnology Incorporated, March 1978.**