CHAPTER 5

SAFETY AND TRAFFIC OPERATIONS

INTRODUCTION

Many factors influence truck safety. Driver performance, roadway design and condition, weather, and vehicle performance directly affects the ability to safely complete a trip. Motor carrier regulations and enforcement affect safety by determining conditions within which drivers and vehicles operate. Within this broad context, however, truck size and weights (TS&W) also directly affects truck safety and traffic congestion, especially in major metropolitan areas. TS&W limits directly impact motor carrers' choices as to the type and configuration of vehicles they operate, as well as the network of roads on which the vehicles are operated. These choices, in turn, determine truck travel patterns and the control and stability properties of the vehicles operated.

There is a shortage of data directly correlating TS&W with the type, frequency, and casualties of roadway crashes. However, available evidence does point to a number of trends relevant to truck safety. Numerous analyses of crash data bases have noted that truck travel on lower performance roads, (e.g., undivided, higher speed-limit roads with numerous intersections and entrances), significantly increases crash risks compared to travel on Interstates and other higher quality roads. Higher traffic densities, which are common in urban and populous areas, exacerbate this problem. The majority of fatal crashes involving trucks occur on non-Interstate, U.S. and State routes, many of which are undivided and have high posted speed limits. For this reason, review of potential TS&W changes should especially focus on truck travel patterns and truck performance capabilities in terms of use on roads of this type.

Further, numerous vehicle performance tests and engineering analyses have frequently highlighted significant differences in the stability and control properties of different sizes and configurations of trucks. Some larger and heavier trucks are more prone to roll over than other, smaller trucks; some are less capable of successfully avoiding an unforeseen obstacle, when traveling at highway speeds; some negotiate tight turns and exit ramps better than others; and some can be stably stopped in shorter distances than others; some climb hills and maneuver in traffic better than others. The effects of these differences on crash likelihoods are subtle, but become more evident when traffic conflict opportunities increase. Some of these concerns can be addressed through judicious designs. Others can only be addressed by matching and restricting use to certain roadways and traffic density conditions. Attention to these inherent properties of trucks is critical when TS&W options are being considered.

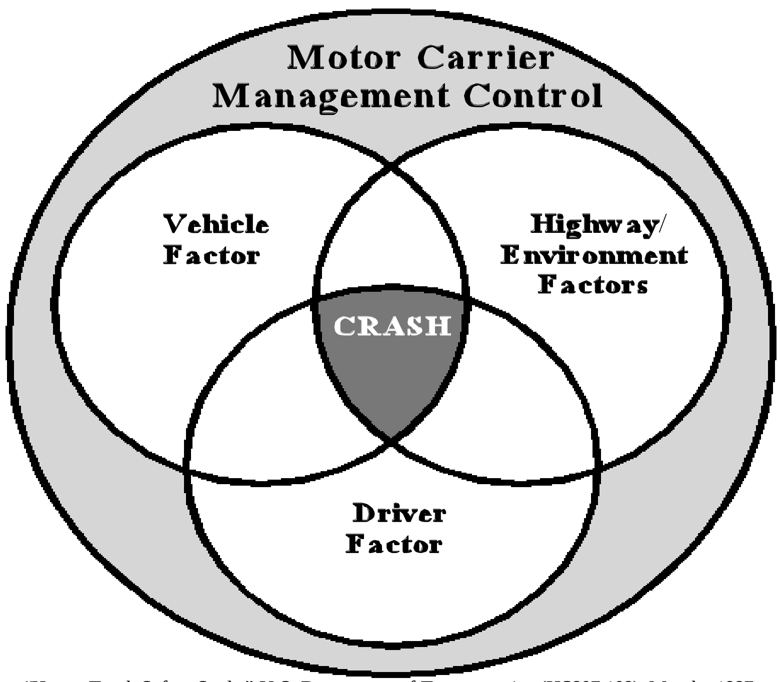
Moreover, notwithstanding any technical and analytical considerations, public perceptions of truck safety, and especially the safety of larger trucks, is uniformly negative. Public opinions on this issue are strongly held and must be heavily weighed when considering TS&W policies.

The following sections provide: additional details about the general causes of truck crashes and the role TS&W plays; more information about the public's and truck drivers' attitudes and opinions relative to large trucks; a summary of the key findings of crash data analyses, and; a summary discussion of the role that the design and performance properties of larger trucks plays in crash causation.

TRUCK CRASH CAUSATION FACTORS

Variables influencing overall crash risk may be grouped into three broad categories: truck equipment, driver performance, operating environment (for example, roadway and weather conditions). Figure V-1 illustrates the complex interrelationship of these variables as they contribute to truck crashes. Almost every crash is initiated by some type of human error, typically a lapse of attention or a misjudgement of situational conditions. For this reason, driver behavior/ performance is overwhelming cited as the principal "cause" of crashes. Equipment considerations including vehicle size and weight as well as mechanical or operational failures play a role smaller than other factors and are very difficult to isolate in terms of crash causation. As the figure indicates, however, other 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. For these reasons it is important to address all the contributing factors to crashes.

FIGURE V-1
INTERRELATIONSHIP OF CONTRIBUTORY TRUCK CRASH FACTORS



Source: “Heavy Truck Safety Study,” U.S. Department of Transportation (HS807 109), March , 1987

Another way of looking at the relationship of the these various factors is to examine a hypothetical "crash causation chain" (see Figure V-2). The chain begins with predisposing conditions, these combine with situational characteristics to create an opportunity for a crash. In other words a set of factors either predispose or enable a crash to occur.

FIGURE V-2
HEAVY TRUCK CRASH CAUSATION "CHAIN"

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

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

CONTRIBUTORY FACTORS

TRUCK EQUIPMENT

Truck equipment issues include physical characteristics, such as the number of trailers, trailer length, and weight capacity; the dynamic performance of the vehicle under varying load conditions[1]; and other mechanical systems such as brakes and engine characteristics.

[1] Includes steady-state roll stability, rearward amplification and load transfer ratio. These concepts are defined in a subsequent section.

The braking capability of combination trucks is a particularly important safety issue. Braking capability relates to achieving a safe stopping distance and maintaining vehicle control and stability during braking and is influenced by a number of factors, weight and size being one. Additionally, rollover propensity, the ability to negotiate turns and maneuver in traffic, and the ability to successfully maneuver when confronted with a potential crash threat are other performance concerns that warrant close attention. This issue is discussed in depth in a subsequent section.

DRIVERS

Driver performance issues, among other things, include skill level, experience, and fatigue. These are critical, regardless of the type or size of truck being driven. In the context of truck safety, the driver may be the most important element of the truck-driver-road-environment relationship. Driver experience and training have an effect on truck crash rates, and the drivers themselves report that inexperience is a significant contributory factor to loss-of-control crashes.

The FHWA Office of Motor Carriers recently sponsored[2] a study to investigate whether longer combination vehicles (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 combination vehicles for two 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.

Preliminary findings suggest that the most significant contribution to a given driver becoming fatigued were the characteristics of the individual driver, the number of hours since the last rest period, and the number of consecutive days of work. Trailer configuration type did contribute to changes in driver performance but these effects were small compared to the principal causative effects. The patterns in driving performance (specifically, lane-tracking) and in fatigue/ physiological recovery and subjective workload generally showed that drivers had the best performance when driving the single-trailer combination; next best was the triple with C-dollies, and poorest performance was with the triple combination with A-dollies.

2 The final report is expected to be completed by the summer of 1997.

OPERATING ENVIRONMENT

Environmental issues primarily include adverse weather, visibility conditions and roadway geometry and congestion. The environment also includes factors such as road class, region of the country, road condition and state of maintenance, and the presence or absence of traffic signals, intersections, guardrails and other barriers, and warning signs. For example, it has been observed that crash rates vary significantly by road class because of design characteristics.

ROADWAY GEOMETRY AND CONGESTION

Roadway geometry refers to the physical structures where trucks operate including road type, grades, and intersections, as well as the interaction of trucks with other users of the roadway and infrastructure. Longer and heavier trucks must contend with intersections, entrance/exit ramps, and highway grades with design elements that may not be suitable for current or alternative sizes, weights or configurations.

The interaction of truck design features with roadway geometry properties and visibility is accentuated as traffic volume increases. There is also a growing recognition that traffic congestion and driver behavior may be related--that congestion may cause more aggressive driving behavior.

ADVERSE WEATHER

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.

Visibility is a function of weather as well as time of day. Dawn, dusk and night place increased operating demands on the driver to safely control the vehicle. Crash profiles illustrated in Table V-1 show that approximately 35 percent of fatal crashes and about 26 percent of non-fatal crashes occur in visibility conditions other than normal daylight.

TABLE V-1
LARGE TRUCK OR BUS CRASHES (IN PERCENT)
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

Clearly 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 driver is critical in initiating or preventing a crash. 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 or unsafe 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 concerns.

Figure V-3 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.

FIGURE V-3
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

For example, perhaps the most prominent impact of environmental variables are the additional driver and equipment performance demands required for safe vehicle operation. As indicated earlier, conditions of poor visibility result in increased operating demands on the truck driver to safely control the vehicle. Sight distance, decision distances, and the time available for corrective or evasive action all are reduced resulting in a need for closer control of the vehicle.

MOTOR CARRIER SAFETY OBSERVATIONS

This section presents an overview of driver perceptions, both of automobiles and trucks.

DRIVER PERCEPTIONS

DATA COLLECTION APPROACH: FOCUS GROUPS

In 1996, as part of this CTS&W Study, FHWA held twelve focus group meetings to research the perceptions, concerns and reactions of the auto driving public and of over-the-road truck drivers[3] to operations in mixed auto and truck traffic. The focus group discussions were intended to generate an in-depth 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 and perceive the greatest threat to come from other auto drivers--people who are impatient, aggressive, reckless, intoxicated or simply inattentive. But they also consistently cited large commercial trucks among their top three or four highway safety concerns.

Truck Size and Weight

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.

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3 FHWA Focus Groups with Auto Drivers and Truck Drivers on Size and Weight Issues, Draft Final Report, Apogee Research, Inc., February 24, 1997.

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. When the focus group participants see or hear examples of 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--drivers with bad attitudes and/or economic forces in the trucking industry that place too much pressure on drivers and inadvertently create incentives for cutting corners and rewarding unsafe practices.

Road Conditions

Also cited as factors for concern were increased traffic congestion, bad weather and the mixing of truck and auto traffic under congested or inclement conditions.

Changes to Truck Size and Weight Limits

The vast majority of participants said they preferred the status quo on Federal TS&W standards, and a return to greater restrictions if any changes were actually made. 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 perceive longer 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 respondent auto drivers doubted 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 ever vigilant against external threats to their safety.

Truck Size and Weight

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 some ramps and access roads along interstate highways.

They 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, speed, fatigue, driver experience.

Sharing the Road

The truck drivers reported that automobile drivers are 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 perceive that traffic congestion is getting worse. They also perceive that the highways are less able to accommodate their larger, heavier trucks, creating 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 who they feel are being rushed through training which more experienced drivers perceive to be inadequate because it focuses on preparing them to obtain a Commercial Driver's License (CDL), not necessarily to be a safer driver.

Changes to Current TS&W Limits

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

Truck drivers generally opposed changing the TS&W standards. The majority prefer 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. They 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 previously cited.

SUMMARY

Automobile, and for that matter, truck drivers clearly have strongly held views about truck safety and larger truck safety and larger trucks. These concerns must be weighted heavily when considering TS&W policies.

CRASH DATA ANALYSES

Differentiating the crash involvement patterns of small subgroup populations of vehicles is problematic. Equally confounding is the effect of the interrelated variables previously discussed, which makes isolating crash rates as a function of TS&W variables a difficult task. The effects, attributable to truck size, weight or configuration, must be isolated from the impact of the driver, other equipment and environmental factors before definitive conclusions can be reached.

Crash data currently available are capable of ascertaining trends in overall truck safety, but are less capable of clearly differentiating trends by vehicle characteristics. Nonetheless, broad distinctions among vehicle types have been noted.

TRUCK-INVOLVED CRASH RATES

Most recently, and illustrative of others that have been completed in the past, is a study of truck crashes in Michigan[4] which isolated differences between crash rates for singles and doubles (all doubles, not just LCVs) in terms of some key variables, such as day versus night, urban versus rural, and limited access versus other roadway types.

That study found that, based on police-reported crashs, singles and doubles have similar crash experience in terms of overall safety performance, but that other differences were apparent when the overall rates were disaggregated by road class, time of day and area type. Doubles had a statistically significant difference in casualty crash rates on lower road types. For doubles, the rate was 5.85; for singles, it was 3.72 crashs per million vehicle miles. Crashs involving doubles on lower type roads also were more likely to result in injury or death.

Differences were also found between rural and urban areas. When all crashs were considered, doubles performed better than singles in both urban and rural areas; but when only casualty crashs were considered, the doubles had similar rates in rural areas but slightly higher rates in urban areas. This was consistent with the usage pattern for doubles, which travel more on the safer limited-access roadways. Similarly for crashs occurring in the daytime versus nighttime, overall rates were lower for doubles than for singles, but for casualty crashs, the doubles had a worse rate during the day.

Doubles rates were higher than singles rates in some specific situations such as one-vehicle involvements on rural limited-access highways during the day, multi-vehicle involvements on rural major roadways during the day, and urban limited-access roadways during the day. The higher one-vehicle crash rate is primarily due to rollover crashes, a crash type for which, the author notes, doubles are well known.

[4] "Differential Truck Accident Rates for Michigan," Richard D. Lyles, Kenneth L. Campbell, Daniel F. Blower, and Polichrous Stamatiadis, Transportation Research Record 1322, Transportation Research Board, National Academy of Sciences, Washington, D.C., 1991.

SEVERITY OF TRUCK-INVOLVED CRASHES

Crash severity is generally measured in terms of whether the crash results in property damage only, injuries, or fatalities. Four factors influence the severity of an crash involving cars and trucks: the type of collision that occurs, the relative size and weight of the vehicles, the change in velocity of the car, and the type of truck involved in the collision.

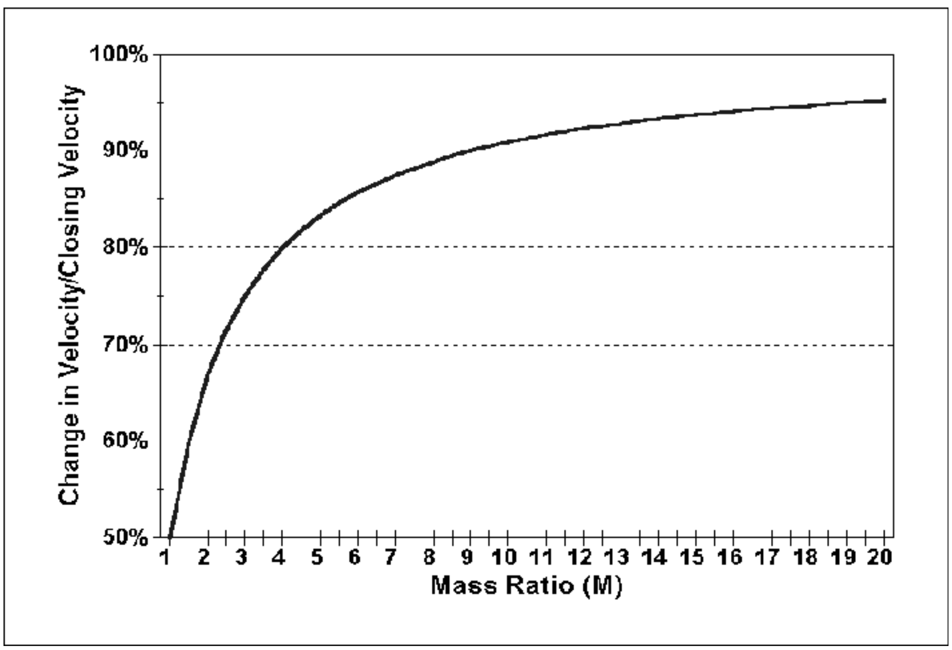
Relationship of Truck Size and Weight to Crash Severity

Safety risk is significantly increased if truck traffic increases in operating environments with a higher risk of truck-car collisions, for example, undivided highways as compared to 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 because the near elimination of head-on collisions also reduces the number of car-truck collisions by about a factor of two.

When two vehicles collide, the speed at which they collide, the mass ratio of the two vehicles, and the vehicular orientation in the collision are the primary determinants of whether a fatality results. The effect of the difference in size between the two vehicles is large. For car-truck collisions, in comparison to car-car collisions, the effect of the difference in weight between the two vehicles increases the probability that fatalities which occur will be sustained by the occupant of the car. For car-truck collisions, the problem is also 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.

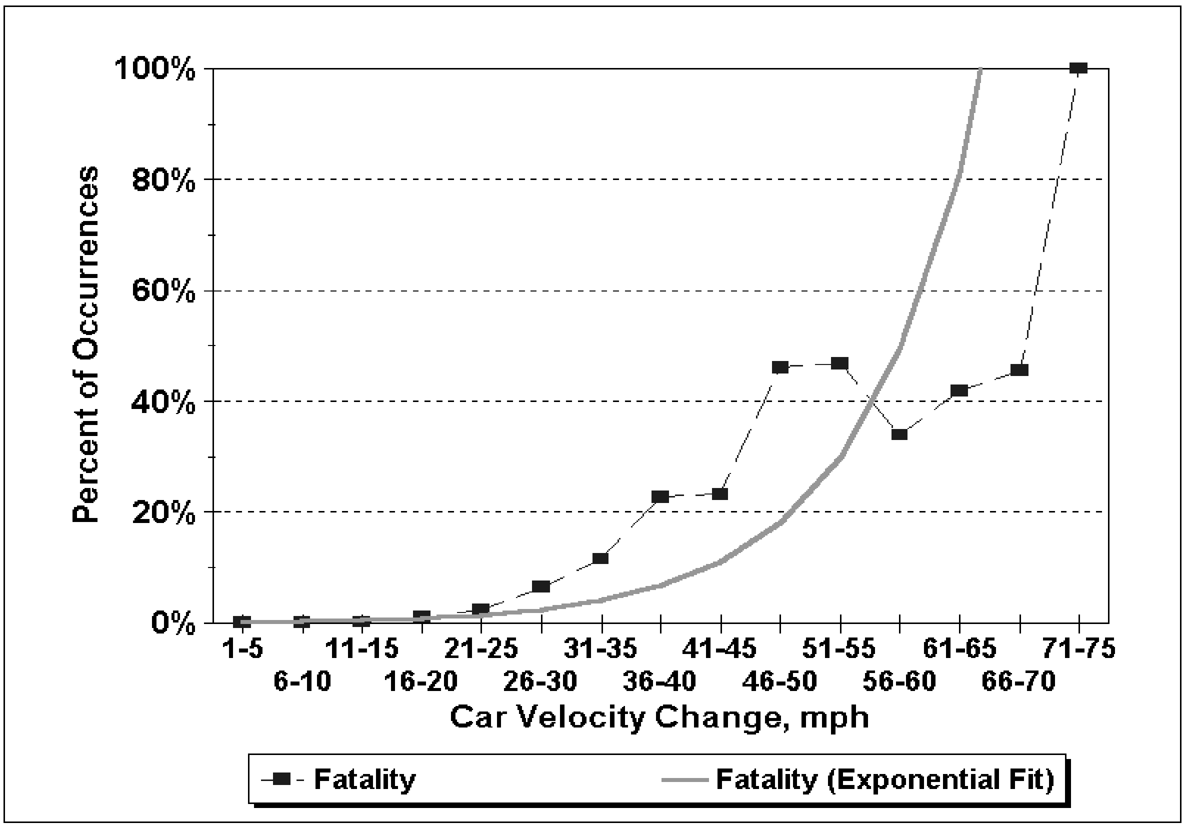
Figure V-4 illustrates the relationship between the difference in size between two vehicles involved in collision (mass ratio) and the relative change in velocity sustained by the smaller of the two vehicles. It assumes an impact between two vehicles of different mass traveling in opposite directions. The vertical axis is 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 vehicle, 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 ratio differences much above 10 to 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 in velocity. At the current 80,000 GVW limit, mass ratio differences between cars and trucks are already on the order of 25 to 1 or higher.

FIGURE V-4
MASS RATIO CHART



The significance of the change in velocity becomes more apparent as it is related to fatality rates in car-truck crashes. The fatality data[5] shown in Figure V-5 indicates the likelihood of a fatality as a function of the change in velocity of the vehicle. These data were compiled from over 19,000 crashes between cars and trucks. 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 typical open highway operating speeds (e.g., above 45 miles-per-hour), car occupants are highly likely to be fatally injured.

FIGURE V-5
CHANCE OF FATALITY AS A FUNCTION OF CHANGE IN VELOCITY



5 "Large Trucks in Urban Areas: A Safety Problem?", James O'Day and Lidia P. Kostyniuk, Journal of Transportation Engineering, 111, 303, (1985).

Relationship of Crash Severity to Truck Configuration

An earlier study[6] (results shown in Table V-2) compared the overall distribution of crash outcomes (fatality, injury, or property damage only) between trucks with single trailers versus trucks with double trailers for both local and intercity trips. Distinctions were not made relative to the travel patterns of the two vehicle types. Crashes involving trucks with double trailers were more likely to result in a fatality, and more so for local trips than intercity trips.

TABLE V-2
DISTRIBUTION OF CRASH OUTCOMES BY TRIP TYPE FOR TRUCKS WITH SINGLE AND DOUBLE TRAILERS (IN PERCENT)

Trip Type	Single Trailer			Double Trailer		
	Fatal	Injury	Property Damage	Fatal	Injury	Property Damage
Local	3.13	73.51	23.35	11.11	48.15	40.74
Intercity	7.52	60.35	32.13	8.60	51.55	39.86
Total*	7.32	61.46	31.23	8.27	50.61	40.75

*Local and Intercity for van-type trailers only. Total includes data for other trailer types.

6 "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.

VEHICLE DYNAMICS ISSUES RELATED TO SAFETY AND TRAFFIC OPERATIONS

Rollovers, maneuverability, and the ability to avoid unanticipated crash threats are all affected by vehicle design characteristics. This section describes how those properties are related to TS&W.

Differing TS&W policies can affect the safety and traffic operations characteristics of heavy trucks because they lead carriers to make differing choices in the basic design properties and configurations of the vehicles they choose to operate. The following is a list of vehicle properties that typically differ as a direct result of differing size and weight allowances:

- Overall vehicle/unit length;
- Vehicle/unit wheelbase and track width;
- Overall vehicle/unit weight;
- Individual axle weights;
- Number of axles on vehicle/unit;
- Number of units in a combination unit vehicle;
- Number of articulation points in a combination unit vehicle;
- Number and type of tires;
- Suspension properties; and
- Brake system properties.

These vehicle design differences, in turn, affect vehicle braking, handling, and stability properties. In some cases, they can limit vehicle performance in traffic and/or incrementally reduce their ability to successfully execute abrupt or extreme maneuvers that tax the performance capability of the vehicle. Unless other compensatory changes in driver performance and/or operating environment demands are made to counteract the effects of vehicle performance differences, crash likelihoods and/or traffic disruption effects increase incrementally.

SAFETY RELATED EFFECTS

Vehicle handling and stability characteristics that can significantly affect the safety of heavy trucks, and which typically differ in relation to differing size and weight policies, include: static rollover threshold, braking efficiency, response of the rear trailer in a multiple trailer combination to rapid steering (rearward amplification), and high speed offtracking.

STATIC ROLLOVER THRESHOLD

Static rollover threshold is the level of lateral (sideward) acceleration that a truck can achieve during turning, without rolling over. Vehicles with low rollover thresholds are prone to rolling over when negotiating exit ramps from freeways, when making severe crash avoidance lane change maneuvers, or when they run off the road. The principal determinant of rollover threshold is the ratio of the center of gravity (COG) height of the vehicle's mass and cargo to one-half the vehicle's track width. Suspension and tire characteristics also influence this property, but to a lesser degree. Rollovers account for 8 percent to 12 percent of all combination-unit 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, especially if hazardous materials are involved.

Rollovers can be reduced by making vehicles more roll stable. Another solution would be for drivers never to exceed posted or reasonable speeds when traversing curves or exit ramps, but past experience indicates this does not always happen. Test procedures are available[7], which involve tilting a tractor and trailer either separately or together, to measure these vehicles' static rollover thresholds. Various minimum performance thresholds have been suggested for this test. Analytical methods of calculating rollover thresholds also exist which could minimize the need to perform tests in all but questionable cases.

Larger, heavier vehicles do not necessarily have poorer performance with respect to this metric than do smaller, lighter vehicles. However, loading more payload onto a given vehicle will in many cases worsen its rollover propensity. On the other hand, various design techniques, principally those that lower the COG of the vehicle's cargo hold, can substantially improve this performance characteristic, regardless of a vehicle's size or weight. The COG height can be reduced by lowering the trailer deck, the legal height limit or both. Also, the trailer could be widened. Other design techniques include adding one or more axles, stiffening suspensions, or specifying stiffer tires. Increasing the width of a typical trailer from 96 inches to 102 inches would improve roll stability 5 percent to 6 percent. Lowering the COG height would have even a more dramatic effect. Going from five to six axles on a 53-foot van semitrailer combination would improve roll stability by 5 percent. For a given freight commodity, decreasing the maximum GVW from 80,000 pounds to 73,280 pounds, the former Federal limit, would improve static roll stability by more than 6 percent.

BRAKING PERFORMANCE

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 jackknifing or otherwise losing directional control due to wheels locking and skidding. Past

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[7] SAE J21280

studies[8] have indicated that brake system performance plays a contributing role in approximately one-third of all medium/heavy truck crashes.

The ability to stop in short distances is primarily dependent upon 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 and poor brake balance. Improper brake balance can cause downhill runaways and braking instability. In addition, adding more load to a given vehicle, without adding axles and brakes, decreases stopping performance.

None of these problems are attributable to a truck's size or weight, they are generic truck safety issues. Properly designed larger trucks have more axles and, therefore brakes, to carry the heavier loads for which they are designed, but braking problems can be exacerbated if brake maintenance is lax.

Antilock braking systems are especially beneficial for heavier multiple trailer combinations because they have more axles/brakes which can be unevenly loaded or balanced, leading to incrementally increased risks of braking-induced instability and loss-of-control.

The National Highway Traffic Safety Administration recently finalized requirements that significantly upgrade the performance of trucks' brake systems and require antilock brake systems on all vehicles. These regulations follow others requiring trucks to be equipped with automatic brake adjusters and brake adjustment indicators. Permissive rules have been enacted to enable longer stroke brake chambers, which stay in adjustment longer than conventional brakes.

The collective effect of all these rule changes will be a significant overall improvement in both as-new and in-service brake system performance. All sizes and configurations of trucks could be expected to achieve these higher performance levels as well, if equipped and maintained as these new rules require.

REARWARD AMPLIFICATION

When a multiple-trailer combination is traveling at highway speeds (55 mph), it is susceptible to having its rear trailer roll over if an abrupt lane change crash avoidance maneuver becomes necessary. Lateral acceleration generated by the tractor, when the maneuver is initiated, is amplified in the trailing units being towed. This phenomenon (rearward amplification) is reduced primarily with increased trailer lengths and fewer articulation points. Other design factors, as well as the vehicle's weight, influence this characteristic to a lesser degree. Instances of these occurrences are rare, primarily because these vehicles (doubles and triples) accumulate less than 5 percent of the total truck mileage, and are typically operated in comparatively benign operating

[8] "Improved Brake Systems for Commercial Vehicles," U.S. Department of Transportation (HS 807 706), April, 1991.

environments. Therefore, they experience comparatively little exposure to crash risk. The number of incidents could be expected to increase, however, if larger numbers of these vehicles were used, particularly in denser traffic that give rise to more frequent traffic conflicts.

The rearward amplification of multiple-trailer combinations can be substantially reduced through the use of double drawbar converter dollies, so-called C-dollies (see Figure V-6). C-dollies employ two connecting drawbars, instead of one, that couple to the preceding towing trailer. This effectively eliminates an articulation point in the combination, which damps out the rearward amplification characteristic. Thus, double combinations end up with two articulation points instead of three, and triples end up with three instead of five. C-dollies improve the rearward amplification of Western (STAA) doubles by 17 percent. Lengthening trailers also reduces the rearward amplification. For example, increasing trailer lengths in a B-train double from 28 feet to 33 feet improves its rearward amplification by 10 percent.

In order for the vehicle to have acceptable low speed offtracking characteristics, the C-dollies have self-steering axles which only move when the combination makes low speed turns. Combinations equipped with these dollies have better low speed offtracking properties than similar combinations equipped with conventional single drawbar A-dollies. Test procedures and minimum acceptability criteria for qualifying the performance of these dollies are available.

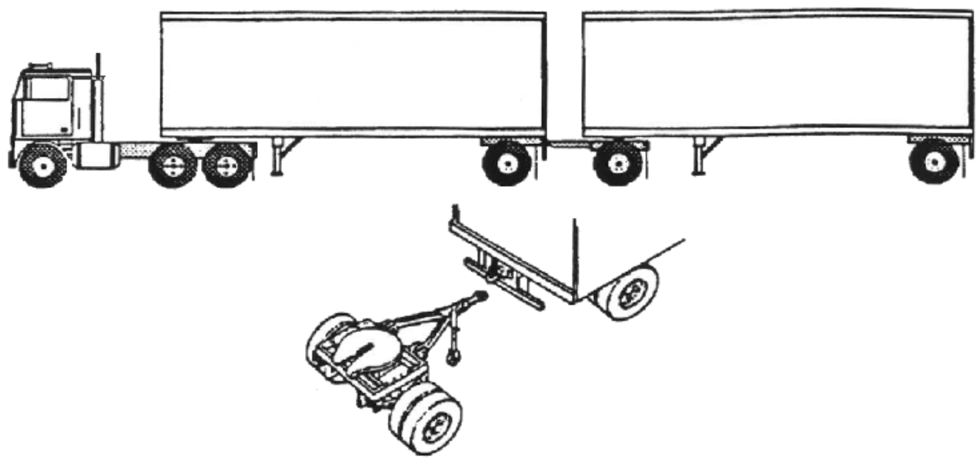
Control strategies involving "intelligent" differential braking have also been researched and show theoretical promise of being capable of effectively dealing with rearward amplification, but commercially viable systems are not currently available.

HIGH-SPEED OFFTRACKING

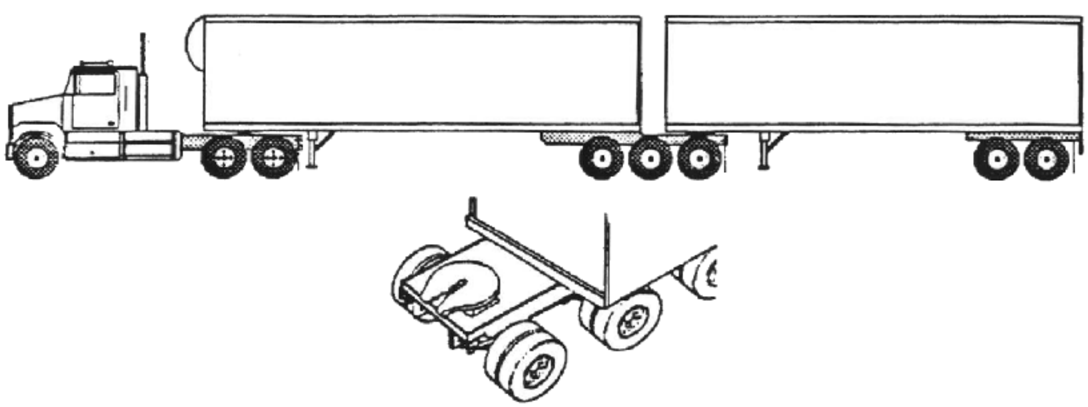
When a combination vehicle negotiates a sweeping (high radius of curvature), high-speed curve, as it would for example at some interchanges between freeways, the rearmost trailer axle can track outside the path of the tractor steering axle. For most truck configurations that have been analytically compared in this regard, this figure is 1.0-foot or less at 55 mph. This tendency is reduced on superelevated curves. Conceivably, if the trailer wheels were to strike the 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. This performance attribute is related to a vehicle's rearward amplification tendencies and is indirectly addressed when rearward amplification is addressed. For a given freight commodity, decreasing the maximum GVW from 80,000 pounds to 73,280 pounds, and thereby the payload, decreases high-speed offtracking by more than 10 percent.

FIGURE V-6
ILLUSTRATIONS OF A, B, AND C TRAIN DOLLIES

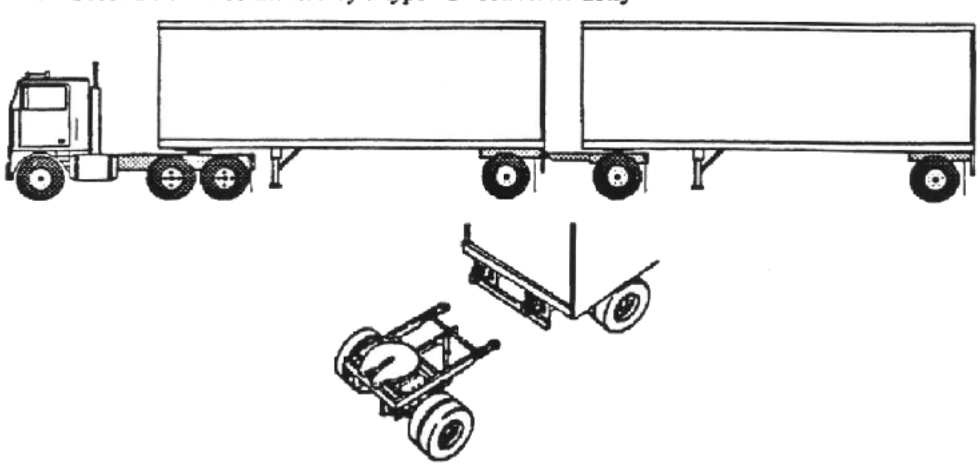
A Train - Second trailer connected with a type "A" converter dolly



B Train - Second semitrailer connects to extended frame of lead semitrailer



C Train - Second trailer connected by a type "C" converter dolly



TRAFFIC OPERATIONS EFFECTS

LOW-SPEED OFFTRACKING

When a combination-unit vehicle makes a low-speed turn, for example a 90 degree turn at an intersection, the wheels of the rearmost trailer axle follows a path several feet inboard of the path of the steering axle of the tractor. This is called low-speed offtracking and may, if excessive, force the driver to swing wide into adjacent lanes in order to execute the turn to avoid climbing inside curbs or striking curbside fixed objects or other vehicles. Also, when negotiating exit ramps, excessive offtracking can result in the truck tracking inboard onto the shoulder or up over inside curbs.

This performance attribute is affected primarily by the distance from the tractor kingpin to the center of the trailer's rear axle which, in the case of a semitrailer, is its effective wheelbase. In the case of multiple trailer combinations, the effective wheelbase(s) of all the trailers in the combination, along with the tracking characteristics of the converter dollies, dictate this property. In general, longer wheelbases worsen low-speed offtracking.

Standard STAA[9] double (two 28-foot trailers), and triple combinations (three 28-foot trailers) exhibit better performance in this regard, compared to a standard tractor/53-foot semitrailer combination, because they have more articulation points in the vehicle combination, and use trailers with shorter wheelbases than semitrailers.

Excessive offtracking can disrupt traffic operations and can result in pavement shoulder and/or inside curb damage at intersections or interchanges heavily used by trucks. Low speed offtracking is a readily measured and/or calculated metric and reasonable acceptability criteria exist with which to control this issue. The extent of offtracking is given in Chapter 6, Highway Infrastructure, for a variety of truck configurations and trailer lengths.

CHANGING LANES/MERGING

Compared to conventional tractor/semitrailer combinations, longer vehicles require incrementally larger gaps in traffic flows in order to merge into these flows. Lane changes in flowing traffic streams would likewise be affected. This could add incremental complexity and burdens to the drivers of these vehicles in these situations. Skilled drivers can compensate for this vehicle property by minimizing the number of lane changes they make and using extra caution when merging, but this may not always be possible. Concern about this performance metric is proportional to the traffic densities in which a given vehicle operates and vehicle length.

[9] Also referred to Western doubles.

HILL CLIMBING/ACCELERATING

As a vehicle's weight increases, its ability to climb hills at prevailing traffic speeds and to accelerate quickly can be compromised if larger engines and/or different gearing arrangements are not used. When speed differentials between vehicles in flowing traffic streams exceed 20 mph, crash risks increase significantly. Table V-3 indicates that crash involvement may be from 15 times to 16 times more likely at a speed differential of 20 mph. On routes with steep grades that are frequently traveled by trucks, special truck climbing lanes have been built. However, these lanes are not always available, making it important that trucks be able to maintain reasonable performance in this regard. Concern about this aspect of truck performance is addressable with strategies combining judicious choices and matching of vehicles to suitable routes and vehicle hill climbing speed and acceleration performance minimums.

TABLE V-3
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.

In the case of multiple-trailer combinations, if single drive axle tractors are used, a situation can arise where the tractor cannot generate enough tractive effort, under slippery road conditions, to pull the vehicle up the hill. Competent, responsible carriers who use routes susceptible to this problem, would not experience repeated incidents of this type without taking corrective actions.

In the past, ameliorative prescriptions for concern about hill climbing performance have centered on requiring larger trucks to be equipped with higher horsepower engines. However, this can be counterproductive, since larger engines tend to consume more fuel and, therefore, cause more gaseous emissions. While in some cases larger engines may be necessary to maintain reasonable performance in this regard, a more straightforward approach is performance standards specifying minimum acceptable speeds on grades and minimum acceptable times to accelerate from a stop to 50 mph, and/or to accelerate from 30 mph to 50 mph.

In cases where frequent truck/car conflicts could be anticipated, either because of the truck's speed maintenance or acceleration performance, or because the number of unsignalized intersections per mile of roadway was high, another countermeasure would be to restrict larger truck use altogether, or to limit their use to certain time periods. Also, in cases where insufficient uphill tractive effort could be a frequent concern, the use of either tandem-axle tractors, and/or tractors equipped with automatic traction control, would be indicated.

TURNS AT UNSIGNALIZED INTERSECTIONS

Heavier vehicles entering traffic streams, on two-lane roads, from unsignalized intersections could take a long time to accelerate up to the posted speed limit. If sight distances at the intersection were obstructed, it might be necessary for approaching vehicles to decelerate abruptly. This could cause crashes or disrupt traffic flows.

The degree to which larger or heavier vehicles perform worse in this regard, compared to smaller trucks, depends on their comparative acceleration performance characteristics. If equipped with appropriate powertrains that ensure adequate acceleration performance, or if routes were screened for suitability, concern about this issue would be minimized, regardless of the size or configuration of the vehicle.

CLEARING THROUGH SIGNALIZED INTERSECTIONS

Longer vehicles, crossing unsignalized intersections from a stopped position on a minor road could increase, by up to 10 percent, sight distances required by traffic on the major road being traversed.

PASSING / BEING PASSED ON TWO-LANE ROADS

Cars passing longer vehicles on two lane roads could need up to 8 percent longer passing sight distances compared to passing existing tractor semitrailers. Longer trucks would require incrementally longer passing sight distances to safely pass cars on two lane roads. In practice, safety conscious truck operators find it impractical to pass cars in these situations, except under the most ideal conditions. Operators of longer/heavier vehicles have to be even more diligent in this regard to avoid potential conflict situations. An alternative countermeasure would be to limit operations of vehicles that require comparatively long times to pass, to roadways with relatively light traffic densities. This issue is discussed further under Roadway Geometry Impacts and Limitations, Chapter 6, Highway Infrastructure.

AERODYNAMIC BUFFETING OF ADJACENT VEHICLES

Air turbulence around trucks does not increase if they are longer or heavier than currently used trucks. However, the gap between the tractor and the semitrailer it tows can be the source of a transient disturbance to adjacent vehicles, if they are operating in substantial crosswinds. Doubles combinations have two of these gaps, while triples have three. Thus, a passing car could experience this transient disturbance that many more times under these conditions. To the extent that motorists now find these occurrences disconcerting, they would experience that feeling incrementally more often if multiple trailer combinations were more widely used.

Truck generated splash and spray is primarily an aerodynamic phenomenon. Thus the incremental concerns that arise relative to buffeting and multiple trailer combinations, would be similar relative to incremental splash and spray concerns.

Efforts to improve truck aerodynamics are continual, since the fuel economy benefits they can yield are substantial. Both buffeting and splash and spray effects will be reduced as these market-driven product development efforts proceed.

SUMMARY

Notwithstanding driver, roadway and weather effects, vehicle size and weight can play a critical, if somewhat subtle role in truck crash causation. Only in cases of a component failure does vehicle performance directly cause a crash to occur, but more importantly, 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. Some configurations of larger trucks have comparatively inferior performance capabilities compared to other configurations of smaller trucks and these differences, especially if frequently challenged in traffic conflict situations, have been shown to result in incrementally higher crash likelihoods.