Truck Accident Studies

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ABSTRACT

Data compiled for most accident reporting systems are typically the result of police accident investigations. Police officers usually have neither the time nor the experience to conduct in-depth accident investigations or collect the necessary data, when trucks are involved, that will allow examination of the relationships between trucks and the roadway environment. When accidents involve multiple deaths or numerous injuries, special police agencies or accident investigation teams may devote the resources necessary to examine truck-roadway environment relationships. Microscopic data, including specific accident investigations, are examined to determine problem areas and to identify vehicle characteristics. Then macroscopic studies and nationwide accident statistics are analyzed to define the potential scope of problems related to trucks and roadway environment. Truck accidents involving runaways, intersections, grade crossings, pavement roughness, barriers, overturns, and wet pavement are examined.

This paper is a compilation of the data on and analysis of many of the in-depth multidisciplinary, heavy-truck accident investigations that have been conducted by the National Transportation Safety Board (NTSB). In particular accidents that involved the truck, its design or operation, and the relationship with the roadway environment were selected for further elaboration. A review was made of the literature and of several national accident data files in order to describe the potential magnitude of problems highlighted during the in-depth investigations.

This methodology is used because most accident data files do not contain sufficient data to allow examination of the human, vehicle, and roadway environmental factors that are involved in an accident. In addition, most accidents are investigated by individuals who either do not have the necessary experience or do not have the time that is required to fully investigate a heavy-truck accident. Sometimes police investigations appear to place too much emphasis on human failure so that blame can be assessed and a citation issued. Often unwarranted citations are issued to truck drivers after accidents for speeding or speed excessive for conditions simply because of the amount of damage caused by the heavier truck. To calculate speeds of trucks involved in accidents, complex analyses are required that often use equations that police are unfamiliar with or incapable of using. There are a lot of factors that may not be accounted for in police investigations, such as tire capability, braking efficiency, and weight shift. Some police officers will not highlight a defect or failure of the roadway environment even if they recognize it because of jurisdictional pressure to avoid liability.

For a similar reason, carriers may not highlight vehicle deficiencies in their report of accidents to the Bureau of Motor Carrier Safety (BMCS). Thus accident files such as the National Highway Traffic Safety Administration's (NHTSA's) Fatal Accident Reporting System (FARS) and the BMCS accident files that are commonly referred to because they are "the best files we have" may be biased because of financial responsibility or limited in scope because of investigative experience and may not provide important information necessary for analyzing complex interrelationships to determine design criteria. In addition, there are usually limited measures of exposure by vehicle type and load configuration that can be correlated with accidents by type of truck and load configuration. Other in-depth accident investigation teams such as California's Multidiscipline Investigation Team (MAIT), Virginia's Crash Team, and NHTSA's National Accident Sampling System (NASS) teams analyze accidents in depth. Only the NASS accidents are computerized, and those accidents may still not provide sufficient data because of lack of heavy-duty experience or evidence that is destroyed or prohibited because of civil or criminal litigation.

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ROADWAY ENVIRONMENT DESIGN TO PREVENT ACCIDENTS

In the past, traffic engineers often designed for 85 percent of the vehicles. As an example, speed limits were posted on the basis of the 85th percentile vehicle. However, in the past, trucks accounted for only 10 percent of the traffic on many roads.

There are specific highway segments that carry a disproportionate amount of heavy-vehicle traffic. At some of the more recent truck accident sites the NTSB investigated, the average daily traffic (ADT), type of road, truck percentage, and truck-involved percentage were as given in Table 1.

One recent report (6) stated that 20 percent of the vehicles on the highway are commercial vehicles. Approximately one-half of these are the common tractor-semitrailers. In an unpublished paper, cited in The Influence of Roadway Surface Discontinuities on Safety (6), an author suggests that trucks will make up 34 percent of the vehicle population, are increasing precipitously in number, and are increasing in size and weight as fast as the technical, economic, and political climates will allow.

Future highway designs for high-volume truck routes will warrant special designs for trucks to provide for safety of motorists. As will be discussed later, the highway design may have to reflect

TABLE 1 Characteristics of Sites of Truck Accidents

ADT	Type of Road	Trucks (%)	Truck-Involved Accidents (%)	Reference
4,400	S.R.	17		(1)
8,871	U.S.	17.8	15.4 semitrucks	(2)
13,000	U.S.	26		(3)
3,500	U.S.	41	21 heavy	(4)
2,650	U.S.	20.9	39.1 truck combinations	(5)

the vehicle conditions and operating characteristics of trucks unless vehicle conditions are improved through state inspection of trucks and drivers. Currently, BMCS is funding a Motor Carrier Safety Assistance Program (MCSAP) in an attempt to improve truck conditions.

Designs and maintenance programs in the future will warrant escape ramps; special traffic control devices; wider, less sharp turning radii; longer acceleration and deceleration ramps; stronger and taller barriers; and better maintained, higher friction surfaces.

CURRENT INVOLVEMENT OF TRUCKS IN ACCIDENTS

The 1983 FARS data indicate that there were 3,301 fatal accidents (out of a total of 37,971 fatal accidents) involving "trucks with trailers." The first harmful event, in these 3,301 accidents, was a collision with another vehicle 72.1 percent of the time. The other leading first harmful events included collisions with pedestrians (8.0 percent), guardrails (2.7 percent), trains (0.5 percent), and overturns (5.4 percent). About 19.5 percent of fatal collisions occur on curves; 17.0 percent on wet pavement; 5.3 percent on snow, slush, or ice; and 78.2 percent where there are no traffic controls. (For comparison, FARS indicates that 39.3 percent of all fatal accidents involved collisions with motor vehicles in transport, 16 percent involved pedestrians, 5.3 percent involved guardrails, 1.1 percent involved trains, 6.5 percent were overturns, and 15.1 percent occurred on wet pavement.)

In 1983 motor carriers subject to the BMCS regulations reported (7) 31,628 accidents ($2,000 or more in property damage). These accidents resulted in 2,528 fatalities, 26,692 injuries, and $342,900,000 in property damage. In 82.1 percent of the accidents the type of truck involved was a tractor-semitrailer. Other types of vehicles involved included single trucks (9.6 percent), tractor-full-semitrailer (3.7 percent), tractor with bobtail (3.2 percent), and truck with full trailer (0.7 percent). Of the accidents involving collisions, 58.1 percent of the accidents and 62.6 percent of the fatalities involved collisions with automobiles. About 17.1 percent of the collisions involved other commercial trucks. Collisions with fixed objects account for 9.7 percent of all truck accidents. Noncollisions account for 25.8 percent of all truck accidents including overturns (8.7 percent), run-off-the-roads (7.7 percent), and jackknives (7.1 percent). Only 0.46 percent of the accidents (145 accidents) involved collisions with trains, which were reported to have resulted in $2,768,000 in property damage. The motor carriers reported that only 5 percent of the accidents involved mechanical defects of which 2 percent were brakes, 1 percent wheels and tires, and 2 percent others.

CHARACTERISTICS OF TRUCKS

Before specific types of accidents are discussed in depth, vehicle factors that are common to many trucks should be examined. These marginal vehicle factors often combine with marginal roadway environmental and human factors and result in an accident. Characteristics of trucks that differ from those of automobiles include, but are not limited to, tires, brakes, height of center of gravity, acceleration and deceleration characteristics, and length and weight. Some of these characteristics are related to each other (e.g., tires and acceleration or tires and braking).

Truck Tires

Truck tires are usually designed for mileage and unfortunately sacrifice traction to achieve longer wear. Typically, the rubber compound is made of hard material that provides less adhesion for stopping. As examples, tests conducted on wet asphalt in which the ASTM skid trailer obtained a value of 0.60 resulted in a corresponding friction value of 0.50 with a truck tire at the same speed. On a wet portland cement concrete surface with an ASTM value of 0.35, a truck tire would be expected to have a friction value of about 0.23. Truck tire traction could be expected to be about 65 to 85 percent of that of an automobile. There are numerous studies (8,9) that relate truck tire traction to ASTM numbers or automobile traction. Figures 1 and 2 show examples of some of the data. One study (8) stated that "Although it is difficult to compare traction measurements made on different pavements at different times, the difference in traction performance between truck tires and passenger car tires in traction performance is very clear."

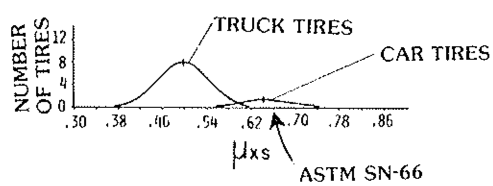

FIGURE 1 Locked-wheel braking on wet asphalt—trucks versus automobiles (8).

Brakes

Truck stopping is further depreciated if brake adjustments are not made at regular intervals. As shown in Figure 3, for one particular type of brake, brake efficiency usually deteriorates rapidly as the slack adjustment begins to exceed 2 in. The maximum available stroke on many large brakes is 2.5 in. Many truck mechanics and drivers state that the front brakes of tractors should be backed off to allow steering in emergencies because a locked wheel slides straight. It is not unusual at the scene of an accident involving a truck to find front brakes on the front wheels either backed off completely or even "capped" to immobilize them. In addition, an accident investigator or vehicle inspector can find other brakes out of adjustment.

Owner-operators of tractors often lease or use company trailers. These truck drivers tend to use trailer brakes in order to save their tractor

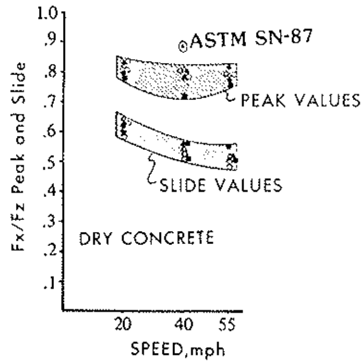

FIGURE 2 Truck tire friction on dry pavement (9).

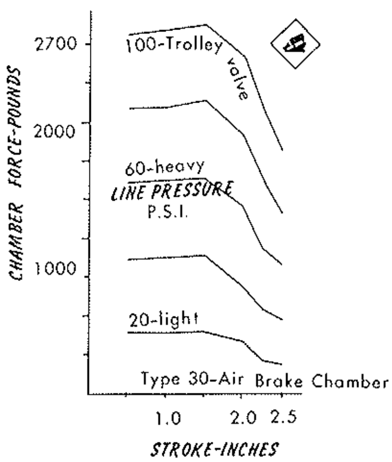

FIGURE 3 Brake efficiency—force versus stroke.

brakes. Lessors may not maintain trailers because of the lack of time the trailer is in their facility, the length of the lease, substantial travel before coming back to the home terminal, or the desire to turn the trailer over to another lessee to make higher profits. Often an investigator will find deficient brakes on trailers.

In BMCS field surveys in 1982, 33,174 vehicles were inspected and 32,510 had violations of the Federal Motor Carrier Safety Regulations (FMCSR). There were 12,564 violations discovered that resulted in a vehicle being placed out of service (38 percent of the vehicles). Brakes accounted for 37 percent of all defects, and 5,946 vehicles (17.9 percent) were placed out of service (10). Another small study examined 190 units to determine the benefits of automatic slack adjusters compared with manual slack adjusters. This study (11) found that one or more brakes exceeded recommended maximum adjustments in 47 percent of the cases with manual slack adjusters and in 42 percent of the cases with automatic slack adjusters. In 15 percent of the trucks with manual slack adjusters and 9 percent of the trucks with automatic slack adjusters the vehicles were placed out of service.

Another study (12) "estimated that more than half of all air braked vehicles have at least one brake out of adjustment and that approximately a fourth of all vehicles have 40 percent or more of their brakes out of adjustment." Many trucks have poorly maintained brakes and the highway engineer should consider designing for actual conditions if improvement in brake conditions is not obtained through other means.

Besides creating longer stopping distances, trucks with deficient brakes create other problems. One phenomenon created by a truck with improperly functioning brakes is weight shift (Figure 4). Weight shift is the transfer of weight from one axle to another. As an example, when an automobile is braked suddenly the front end dips down because of additional loading on the springs and shocks. If a vehicle has brakes that retard equally on all of its wheels, weight shift can be ignored. During braking of a tractor or trailer the lack of brakes on an axle in front of the center of gravity causes weight shift to axles that cannot dissipate energy. As an example, a bobtail tractor without front brakes might only have an effective friction value of 0.34 compared with 0.40 assuming even weight distribution. This is an additional reduction of braking efficiency of about 15 percent due to weight shift (13).

On steep long downgrades improperly adjusted brakes place higher demands on functioning brakes. This results in a buildup of heat in the brakes and the brakes may begin to fade, which can result in a runaway truck. When the pavement is wet, improperly adjusted brakes can result in uneven braking that will cause a truck combination to jackknife.

The California Highway Patrol (CHP), the Bureau of Motor Carrier Safety, and the National Transportation Safety Board have investigated numerous accidents that were caused by deficient brakes. Former California Highway Patrol leaders have helped to form the Commercial Vehicle Alliance (CVA). The CVA and the BMCS are now promoting a national inspection program (MCSAP) that emphasizes checking of brakes and drivers' hours of service (for fatigue) because these are the two most common casual factors highlighted by inspections and accident investigations.

Overturns

The center of gravity of loaded tank trucks, flatbed trucks loaded with high loads, or concrete trucks may approach 70 to 80 in. off the ground. These vehicles may overturn when centrifugal forces on the vehicle exceed 0.24 to 0.45 g's. In addition, tank trucks may experience liquid surge and trucks carry-

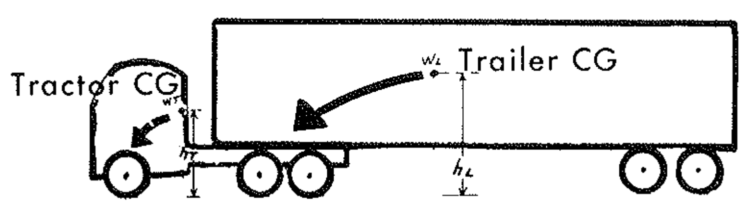

FIGURE 4 Weight shift.

ing meat may have swinging meat, which add additional unstable forces that tend to turn vehicles over.

Acceleration

The acceleration capability of empty trucks may be as slow as 2.0 ft per second per second. Loaded trucks will be even slower, especially on hills. This creates problems for truckers turning onto high-speed roads from intersections where acceleration lanes, if they exist, were probably designed for automobiles. If intersections are tight, trucks may have to turn into the high-speed lanes. At rail-highway grade crossings some trucks are required to stop and are prohibited from changing gears. Depending on grade and load, a truck may be restricted to first or second gear. This may translate into a maximum speed of 5 to 10 mph. This increases exposure time significantly, especially if two or three tracks are involved.

Other characteristics identified during NTSB accident investigations included overhanging loads that swing into opposing lanes on turns. Finally, the additional load on trucks compared with automobiles increases kinetic energy of the vehicles to 20 times that of automobiles used to test barriers and renders most guardrails ineffective.

NTSB INVESTIGATIONS

In the past, because of limited staff, NTSB has investigated only the more spectacular highway accidents. Many of these accidents involved large trucks and resulted in large amounts of property damage or numerous fatalities. The accidents NTSB investigated were not representative of any population, except perhaps to show the extent of the most serious accidents. When several accidents of any one type are viewed together, patterns begin to emerge.

Runaways

In the late 1970s NTSB investigated many runaway accidents involving trucks that had lost brakes because of heat fade or deficient brakes (14-17). Usually when a truck runs away the driver tries to change gear and misses, leaving the runaway truck in neutral. In four of the accidents grades were 1 to 4 mi long and from 1 to 10.6 percent. In three of the cases about half of the brake adjustments exceeded 2.125 in. In the other accident brakes on a trailer were jury rigged with nails and wire.

Roadway designers have addressed many problem locations by adding truck pullout areas and escape ramps. The only areas where problems may still exist are short steep grades approaching urban areas. NTSB highlighted this problem to the FHWA that determined that crash attenuators or other devices that do not require a long runout are not feasible. This may be a problem because many small urban areas developed near water and are located at the bottom of steep hills or because urban areas expanded to include steep hills. In this scenario trucks could run away striking automobiles that might be stopped for a traffic signal at the bottom of the grade. It is hoped that pedestrians, patrons of adjacent businesses, and residents will not become involved.

Recently, in June 1985, a truck in Van Buren, Arkansas, missed two signs (another large sign had been removed by a sewer contractor) and ran away down a 1,900-ft-long hill on which trucks were prohibited. The truck struck a station wagon and pushed it through a guardrail and two historic brick buildings, after which the wagon ignited. Nine people were killed and three buildings burned to the ground. At this location, standard signing has not worked.

Intersections

Intersections, especially those near some industrial areas, are another problem area for trucks. Trucks not only have deceleration problems, discussed previously, they also have acceleration and turning problems. NTSB investigated an accident in the timber belt that involved a truck transporting 80-ft-long pine logs that was making a turn into a pulp mill (18). As the truck turned right onto the crossroad, the rear of the logs swung out into the opposing lane and ripped through an oncoming school bus. Three students were killed. Special precautions are warranted for trucks near some industrial areas such as timber operations, hazardous material users, steel fabricators, or other large-commodity users or producers.

In another accident (19) an empty truck turned a corner and in 927 ft had accelerated to about 42 mph when it was struck in the rear by a bus. The highway had a speed limit of 55 mph and the bus was going 5 to 10 mph over the speed limit when the collision occurred. Speed differential of vehicles has been cited in numerous studies as contributing to conflicts that often result in accidents. At this accident site the acceleration lane was marked to be 345 ft long; the original design was for 575 ft; and AASHTO standards at the time of the accident called for a 900-ft-long acceleration lane. This empty truck on a 0.8 percent upgrade could accelerate to only 42 mph in 1,927 ft. The particular state where the accident occurred allows vehicles to drive on the shoulder, but a better solution may be longer acceleration lanes.

Grade Crossings

Rail-highway grade crossings are a special type of intersection. Although a few highway departments do not pay much attention to grade crossing accidents because they represent only about 1.3 percent of the nation's fatalities on highways, grade crossing fatalities represent more than half the fatalities to the railroad industry (575 versus 498) (20). A recently investigated accident (21) highlighted the problems at crossings for trucks such as lowboys, "Nu-Car" carriers, or house trailers that may become hung up due to the profile of the crossing. This type of accident appears to be occurring more frequently as roads and rails are raised during periodic maintenance. Recently an FHWA-sponsored committee that assessed grade crossing research needs highlighted this problem as a high priority. A proposal to study this problem is currently being considered by the NCHRP.

The NTSB recently investigated several accidents that involved trucks at crossings that were equipped with crossbucks only. Audibility tests showed that in most large trucks the horn of a high-speed train could be heard only 1 to 2 sec before impact. In several accidents the large side mirrors of the truck blocked the driver's view of the approaching engine--the most conspicuous part of the train. In another accident (22) a truck approaching a crossing at 25 mph needed 104 ft to stop short of the crossing, but the driver could not see the crossing until 88 ft before the crossing.

In two recent accidents both trucks had front axles with inoperable brakes and the rear-axle trailer brakes of one of the trucks probably were not working. If the truck drivers had seen the trains they might have been hampered severely in trying to stop the trucks, especially the driver of the truck loaded with gravel on a timber bridge deck on a 9 percent downgrade approaching the crossing. This 1984 accident alone resulted in $3 million in property damage, more than what carriers reported to BMCS in the 145 train-involved accidents in 1983.

The NTSB previously published a study (23) that described some of the problems of trucks transporting hazardous materials. These vehicles are required by the BMCS to stop before every grade crossing even when lights are not flashing at those crossings equipped with flashing signals. Trucks that stop cannot shift gears when crossing the tracks, which limits top speed to 5 to 10 mph. In one accident (24) on a 5 percent upgrade, the manufacturer calculated that it would have taken the loaded truck 23 sec to cross the single tracks. High-speed trains cannot be detected easily when they are half a mile away and drivers have to make a decision, especially if visibility is restricted by weather, vegetation, or buildings. At active crossings some signals provide only 20 sec of clearance time before the arrival of a train. This has resulted in collisions and in trucks breaking gates when the gates descend on tank semitrailer manhole covers and are pulled forward by the moving truck.

Goodell-Grivas, Inc., has recently completed a study (25) for FHWA that addresses many of these issues. This study recommends that trucks and school buses not be required to stop at active crossings unless the devices are flashing. Active devices are recommended for installation near hazardous material depots and storage facilities, and research is needed to determine the adequacy of the 20-sec advance warning for double- or triple-bottom tractor-trailer combinations.

Trucks are a serious concern at grade crossings because of many of the problems previously cited. The 1983 data of the Federal Railroad Administration (FRA) indicate that 31 percent of all grade crossing accidents involve trucks. About 7.5 percent of the grade crossing accidents involve "truck-trailers." NHTSA-FARS data indicated that 4.2 percent of the fatal accidents at grade crossings involved combination trucks, 2.5 percent involved "other trucks," and 23.4 percent involved pickups. These two data bases may not be comparable because the FRA's data involve many injury accidents. Drivers of large trucks are more likely to survive a grade crossing accident than are pickup drivers if the rear of the truck or the trailer is struck.

Pavement Roughness

NTSB has investigated two truck accidents that may have been related to pavement roughness. One accident (26) involved a 1- to 1.25-in. depression that had been dug out and replaced. When the truck rode over the depression the tractor's tandem equalizer beam failed and the truck overturned on a guardrail that punctured the gasoline tank and resulted in ignition. In another accident (27) a truck broke its right bogie leaf spring assembly about a mile or two after running over a rough section of pavement. This pavement may have helped strain the spring to such an extent that any minor pavement irregularity could have resulted in the fracture of the spring. When the spring broke, the truck, which included a tank semitrailer, went into an uncontrollable left turn and overturned on a concrete median barrier. The high center of gravity of the trailer and the broken spring in combination with the concrete median barrier enhanced the probability of overturn.

In one recent report, cited in The Influence of Roadway Surface Discontinuities on Safety (6), it was stated that

> Perhaps the one area of possible influence that has not been well addressed in the literature is the significance of special wavelengths of road roughness to which trucks may be sensitive. It is known among experienced truckdrivers that certain long wave undulations, as typified by pavement settlements in bridge approach areas, may be peculiarly difficult to negotiate with commercial vehicles, particularly tractor-semitrailers. These features tune to the low-frequency rigid-body bounce and pitch modes of these vehicles. Because the drivers are located near the extremities of the vehicle (far from the center of gravity), large displacement vertical and fore-aft motions can be imposed on the driver, thus complicating the task of maintaining control when negotiating these road features. There is anecdotal evidence that truck drivers have experienced control problems reflecting on safety due to these effects, but there has been no known effort to compile statistics quantifying the magnitude of this particular problem. Unfortunately, available accident data are not specific enough in their recorded detail to provide that answer.

Barriers

In two accidents (27,28) trucks climbed over or overturned on concrete barriers. In one accident (27) the truck climbed over the barrier at each successive joint as the wheels broke through the barrier that was not reinforced through the joints. In the other accident (28) a full truck-trailer's tank trailer flipped over the 32-in.-high barrier. From other accidents (29) it has become clear that trucks "blow-through" guardrails and many steel bridge rails. Work being conducted at the Texas Transportation Institute (30) to design barriers capable of restraining trucks for use in selected locations is promising.

On the basis of the testing this author has seen and studied, he would encourage the use of longer test sections to determine what occurs during secondary and tertiary impacts against the barrier. The author is also concerned that the typical concrete median barrier section may have a tendency to break or dislodge the tractor's front axle, which will disable the truck's steering and stability. Although the guardrail usually provides little protection to trucks, a recent (March 1985) low-speed accident involving a school bus overturn on an 8 percent upgrade in North Carolina could have been prevented if a guardrail had been in place in front of the 63 percent slope that has a 24-ft drop.

Overturns

The FARS indicates that 5.4 percent of accidents involving trucks with trailers are overturns. The motor carriers reported to BMCS that 8.7 percent of accidents are overturns. The NTSB has investigated numerous accidents (31-33) that involved tank trucks and loaded flatbeds overturning on curves. In one accident (31) a driver of a propane truck traveling at 25 mph flattened a 119-ft-radius curve to 184 ft.

When the truck driver took corrective action to avoid an oncoming vehicle the truck overturned. In another accident (32) a gasoline truck traveling 55 to 60 mph overturned on a curve. The only speed guide was a 50-mph speed limit sign. This truck driver was also taking the curve a little wide and sharpened the turn as the truck approached another vehicle, only to overturn.

In Denver, the inexperienced driver of a semitrailer truck, which was carrying Navy torpedoes, going from one Interstate to another missed a 25-mph advisory speed and other visual cues and overturned at 42.5 mph (33). A California study (34) examined 131 tank truck accidents and found that tank trucks have three times the rate of overturns of other trucks for fatal and injury accidents and six times the rate of other trucks for property damage accidents. About 50 percent of the accidents were on curves or ramps, and tank truck accident rates were twice as high as those for other trucks at night. Two-thirds of the speed-related accidents involved overturn on a curve where the speed of the vehicle was 55 mph or less. Only 14 percent of the overturn accidents involved speeds greater than 55 mph.

Several publications by Erwin (35,36) give an indication that some trucks overturn at 0.24 to 0.45 g's. Researchers and AASHTO (37) often believe that the side friction values of 0.12 to 0.30 that are used for roadway design are sufficient. Some even state that motorists will accept a higher level of discomfort on low-speed streets with intersecting traffic, perhaps as high as 0.30 g's at 20 mph.

As cited in the NTSB investigations, truck drivers take curves flatter initially and tighten up the radius of the curve later. This phenomenon was observed in studies involving passenger vehicles by Glennon (38) in the early 1970s. Glennon's data for a 7-degree curve (818-ft radius) show that the average minimum radius driven was 691 ft and the 85th percentile radius was 645 ft, 21 percent sharper than what was designed. Data on the radii truck drivers use on curves on ramps need to be collected.

Not only do some trucks have a low threshold for overturn and drivers turn curves sharper than the design for the curve, but trucks are also susceptible to yaw divergence or instability. "Yaw divergence will lead to rollover in the absence of corrective steering action or reduced speed. Yaw instability manifests itself as the tendency of a vehicle's heading to diverge or increasingly point away from the direction of travel" (39).

Griffith and Gillespie (6,p.38) state that

> By the nature of the way in which the load is carried, and the way in which the roll resistance is shared among axles on commercial vehicles, their turning performance is most often limited by loss of cornering force on the rear axles of a truck or tractor. When this occurs, spin-out follows, with a subsequent risk of rollover. The loss of cornering force is, in part, a function of the road surface and its friction level. In pure cornering maneuvers, the threshold of instability occurs at rather moderate slip conditions (3 to 5 degrees of slip angle), where the cornering force properties are much more dependent on the stiffness of the tire carcass than on the tire-road coefficient of friction. However, when braking is also combined with cornering, brake slip at the rear wheels will contribute to loss of cornering force and subsequent jackknife. Consequently, the potential for this type of accident is greatest when the vehicle is unloaded or when the tire-road coefficient of friction is low.

This phenomenon will occur at about 0.20 g's if the center of gravity is about 80 in. and the speed is 40 mph. The greatest deterrent to yaw instability is superelevation, which eliminates the problem under normal conditions (39).

The author's concern in this area is whether roadway designers can provide enough margin of safety to truck drivers with curve advisory signs. In addition, the author is concerned that at intersections and on merges roadway designers may taper down or completely eliminate superelevation at critical locations, perhaps where the tank truck is beginning to turn a sharper radius than that which was designed.

Wet Pavement

The 1983 FARS data indicate that trucks are slightly overrepresented in accidents on wet pavement compared with all other vehicles (16.7 versus 14.4 percent). Trucks tend to be susceptible to jackknifing on wet pavement because of lower lateral resistance. In 1977 the Safety Board investigators suspected that an empty truck might have hydroplaned before striking a van (4), but researchers claimed that trucks could not hydroplane because of the high air pressure in their tires. Recent research (W.B. Horne, Tractor-Trailer Jackknifing on Flooded Pavements, working paper for TRB Committee A2B07, January 1985, and 40) indicates that trucks can hydroplane and that the old formula should be adjusted to account for the pattern of truck tires. A truck tire at 40 to 100 psi will hydroplane at between 50 and 60 mph. Typically, at more than 55 mph a truck tire will not dynamically hydroplane without combining effects of viscous dynamic hydroplaning. The combined effects decrease cornering ability. When vehicles encounter flooded surfaces, drivers must react with proper steering input quickly and accurately and correct when coming out of the flooded surface, otherwise directional control will be lost.

Forces due to flooding can easily approach 750 lb at 60 mph when there is ponding. This type of condition can create large turning moments that can jackknife a vehicle.

The NTSB has investigated two accidents involving empty trucks on wet pavement. In one accident (4) the roadway had an inconsistent crown with a flat spot 50 to 100 ft before impact on a 3.7 percent upgrade. In this accident the truck driver lost control. In a recent accident (2) involving an empty truck, unbalanced braking caused jackknifing to occur when the truck driver hit the brakes. For this accident the University of Michigan Transportation Research Institute's T3DRS:V1 simulation was used to examine the braking of the truck on wet pavement. A truck can jackknife fully in less than 5 to 6 sec on wet pavement. The model also indicated that trucks with balanced brakes jackknife when braked because of the tractor's proportioning valve or the 2 percent cross slope, or a combination of the two. The model showed that the truck would not have jackknifed on a high-friction surface even when the surface was wet.

NASS data were analyzed to determine if empty trucks are more susceptible to accidents on wet pavement. Unweighted and weighted samples indicated that empty trucks tend to be in accidents on wet pavement more often than loaded trucks. Table 2 gives the NASS data for the weighted samples.

Past studies (41,42) have also highlighted that trucks are involved more frequently in accidents on wet pavement. On the basis of 1977 BMCS data one researcher (41) noted that wet and snowy pavements raised the accident rates of all trucks on all

TABLE 2 Involvement of Trucks by Load in Accidents on Wet Pavement

Load Weight (lb)	No. of Accidents on Wet Pavement	Other Accidents	Percentage on Wet Pavement	Loaded or Unloaded
0-2,500	17,321	62,668	21.65	Unloaded
2,600-10,000	4,073	19,010	17.65	Loaded
10,100-30,000	3,869	22,030	14.94	Loaded
30,100-80,000	4,331	26,270	14.16	Loaded
80,100 or more	36	1,392	2.52	Loaded
Unknown	13,140	89,732	14.64	
Total (average)	42,770	221,102	(16.21)	All

roads. Road surface condition was found to accentuate the effect of day or night such that wet snowy roads at night often had a particularly serious effect on singles and especially on doubles. The other study (42) indicated that the probability of occurrence of jackknifing before an accident, compared with the probability of its nonoccurrence, is about ten times greater on a wet road than on a dry road. Another study (6,pp.38-39) stated:

> The effect shows up in the accident statistics such as the 1980 FARS data for tractor-trailers and doubles. Taking the 10,000- to 30,000-lb weight as indicative of unloaded vehicles, and the 50,000- to 70,000-lb weight as typical of loaded vehicles, the statistics can be summarized as follows:
>
> 1. On dry pavements jackknife is involved in about 7 percent of all fatal accidents of loaded combination vehicles and about 10 percent of those for unloaded vehicles, and
> 2. On wet, snowy, or icy roads the jackknife involvement increases to nearly 17 percent for loaded vehicles and 28 percent for unloaded vehicles.
>
> Thus from the standpoint of tire-road friction coupling, it is concluded that the safety performance of large commercial vehicles is uniquely critical on roads contaminated with water, ice, or snow. The threat to large vehicles under these conditions arises from the potential for loss of control, thus leading to more severe accidents; even at low speeds including jackknife or rollover accidents.

Trucks are overrepresented in accidents on wet pavement. Further study using computer models should be conducted to determine the effects of cross slopes and marginal levels of friction. Both the vehicle and the surface components of tire traction and braking should be improved.

Miscellaneous

Many reports are contradictory and results are confusing, often because vehicles are lumped together. For example, one study (43) indicated that tanker trucks had low accident rates when empty. The higher center of gravity and the potential to overturn when loaded may cause this result. Another study (44) stated that certain attributes of combination trucks might create a high risk especially when traveling empty. Still another study (45) stated that empty combination trucks, particularly empty doubles, had a substantially higher accident involvement rate than did loaded combinations. Accident types, exposure data, and conditions should be separated and studied individually. In addition, better statistical control is needed to avoid contradictory results.

Another study (46) suggested that truck drivers represent a more experienced segment of the driving population and therefore may react differently in potentially hazardous situations and thus may not warrant 2.5 sec of perception and reaction time. In the truck accidents NTSB investigated, cumulative or short-term fatigue, experienced by long-distance truck drivers who may be bored or tired, indicates a need for longer reaction times.

NUMEROUS FACTORS

One of the first accidents the author investigated involved a gasoline truck (high center of gravity), a 720-ft-long 12.6 percent downgrade, and a curve of 117- to 100-ft radius at the bottom of the grade followed by a railroad track with activated flashers and stopped vehicles. The truck overturned and burst into flames. The driving task was perhaps too great, and an accident was imminent. Accidents often occur when vehicle, human, and roadway environmental factors are deficient or marginal.

CONCLUSIONS AND RECOMMENDATIONS

1. Future heavy-truck populations on some specific routes will warrant additional roadway designs for trucks.
2. Trucks often have deficiencies that may have to be accounted for in roadway and vehicle designs because of the frequent occurrence of such deficiencies, including
   - Truck tires provide low friction levels;
   - Brakes, especially front brakes, are not functional in 30 percent or more of the vehicles inspected depending on the study cited; and
   - If trucks have nonfunctioning brakes, the load may undergo a weight shift to those wheels that would further depreciate braking capability.
3. Good solutions for runaway trucks on short steep grades approaching populated areas with limited land for escape ramps have not been developed.
4. Intersections adjacent to special industries such as wood or steel mills may need to have special turning ramps to eliminate load entry into adjacent lanes.
5. At grade crossings trucks have special problems and crossings may have to be designed for trucks near some industries. Trucks have audibility, visibility, low clearance, acceleration, and exposure problems at grade crossings.
6. Pavement roughness may cause uncontrollable loss of truck steering due to broken springs, flat tires, or other components.
7. Most barriers placed before the early 1970s are ineffective in redirecting a truck.
8. Trucks overturn frequently and may turn over when centrifugal loads exceed 0.24 to 0.45 *g*'s if the driver can drive at the design radius of the curve. Often a driver creates a sharper radius.
9. Trucks are overrepresented in accidents on wet pavement and tend to jackknife under many conditions, such as unbalanced braking, lack of brakes, or on low-friction surfaces, and can hydroplane when lightly loaded.

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