Comprehensive Truck Size and Weight (TS&W) Study

Phase 1-Synthesis

Traffic Operations

and

Truck Size and Weight Regulations

Working Paper 6

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1.0 Technical Relationships of Policy Consequence Concerning Traffic Operations

Truck size and weight regulations affect the numbers, physical characteristics, load characteristics, and operating capabilities of trucks on highways. These factors affect highway capacity (expressed in terms of the total number of vehicles a facility can handle) and the level of service experienced by highway users. This paper examines these effects.

As a precursor to the development of technical relationships between truck size and weight issues and operational considerations, this paper first describes some of the general concepts and definitions associated with traffic operations and heavy trucks.

<u>Highway Capacity:</u> In designing highways, traffic engineers must anticipate the amount and type of traffic that will travel on the road in order to make the highway match its anticipated use. A highway's capacity is defined as the number of vehicles that can reasonably be expected to pass a point or section of the highway during a given period of time under prevailing roadway, traffic, and control conditions. Highway capacity is usually expressed in the number of vehicles per hour.

<u>Level of Service:</u> The concept of level of service describes operating conditions within a traffic stream, and their perception by motorists and passengers. A level-of-service definition generally describes these conditions in terms of such factors as speed and travel time, freedom to maneuver, traffic interruptions, comfort and convenience, and safety. The *Highway Capacity Manual* (TRB; 1985) defines six levels of service. They are given letter designations with level-of-service A representing the best operating conditions and level-of-service F representing the worst.

<u>Passenger Car Equivalent:</u> Since trucks and other heavy duty vehicles are larger than cars, typically have less acceleration and require more room for maneuvering, lane changing, and braking, they consume more of the highway's capacity. Traffic engineers account for the impact on capacity from large trucks and other heavy duty vehicles by assigning each class of vehicle a passenger car equivalent (PCE) value. This PCE represents the number of passenger cars that would consume the same percentage of the highway's capacity as the vehicles under consideration under prevailing roadway and traffic conditions.

As discussed later in this paper, the PCE value of a truck depends on its weight, length, engine, and other vehicle characteristics. The PCE value also depends on roadway characteristics such as number of lanes and the length and steepness of grades.

Power The maximum power that an engine can deliver is related to vehicle performance capability in accelerating and maintaining speed on grades. Power is typically expressed in units of horsepower. The power actually used by a motor vehicle for propulsion can be determined from the following equation:

$$P = 0.00267 * R * V$$

where

- P = power actually used (horsepower)
- R = sum of resistances to motion, including rolling, air, grade, curve, and inertial resistances (pounds)
- V = vehicle speed (miles per hour)

The maximum power output available for propulsion at a given engine speed equals the maximum gross brake horsepower at the flywheel for that engine speed less the power consumption of engine accessories, such as water pumps, generator, etc. For large trucks, 94 percent of the manufacturer's nominal horsepower rating is typically available for propulsion. (Institute of Traffic Engineers; *Traffic Engineering Handbook*; 1992)

1.1 Speeds on Grades

Trucks typically accelerate more slowly and experience greater difficulty in maintaining desirable speeds on long, steep upgrades than automobiles do. Truck characteristics affecting speed on upgrades include operating weight, horsepower, aerodynamic resistance, drive-train-to-gear ratios, and tires.

Speed reductions on grades present special problems on two-lane roads in hilly or mountainous terrain where passing opportunities are limited. Queues of vehicles may form behind slow-moving trucks on upgrades. Under such circumstances, drivers of other vehicles may be encouraged to undertake passing maneuvers under unsafe conditions.

The gross weight of a vehicle (in pounds) divided by its power (in horsepower) has been used by analysts for making approximate performance comparisons among different types of vehicles, in terms of their ability to accelerate and maintain speeds on upgrades. Estimates of the relationships between hill-climbing speed and weight-to-horsepower ratio from the *Highway Capacity Manual* for typical trucks are shown in Exhibit 1. In general, as a truck's gross vehicle weight (GVW) increases, its acceleration capability decreases unless horsepower or other truck characteristics are also improved to compensate for the weight increase. However, since the power available for propulsion depends on engine condition and size, transmission arrangement, and engine speed, the weight-to-horsepower ratio is an imperfect measure of the ability of a truck to maintain a given speed on a given grade. As a result, states with special gradeability requirements for heavy trucks will generally express these requirements in terms of speed maintenance rather than weight-to-horsepower limits. For example, in its model regulations for longer combination vehicles (LCVs), the Western Highway Institute states that LCVs should have the ability to maintain a speed of 20 miles per hour under normal operating conditions on any grade over which the combination is to be operated.

Meyer (1992) found that, of the 20 states that routinely issue permits for longer combination vehicles (LCVs), 13 had minimum operating speed requirements for LCVs on the roads over which they operate: 15 miles per hour in 3 states, 20 miles per hour in 5 states, 40 miles per hour in 4 states, and 45 miles per hour in 1 state. An alternative approach that might be considered is to specify minimum operating speeds in relation to the speed limit. For example, regulations might require that trucks on grades be capable of operating within 20 miles per hour of the speed limit. Exceptions might be made for roads with special hill-climbing lanes that keep slow-moving trucks on grades from reducing the level of service for other traffic.

Vehicle length and type of configuration do not significantly affect speed on grades. However, longer trucks are more difficult to pass, which may exacerbate weight-related problems with speeds on grades.

1.2 Merging, Weaving, and Lane Changing

In addition to speed impacts on grades, substantial increases in truck weight could lower truck acceleration capability, thereby making it more difficult for trucks to merge, weave, or change lanes on highways. Exhibits 2 and 3 illustrate the relationship between weight-to-horsepower ratios and acceleration capabilities of heavy vehicles. Inadequate acceleration of heavy trucks as they merge with other traffic on freeways could cause the travel speed of existing traffic to slow, thereby reducing the effective highway capacity, degrading the level of service and intensifying the need for other vehicles behind the merged trucks to change lanes or brake.

Exhibit 1. Truck Hill-Climbing Speeds as a Function of Weight-to-Power Ratios

Percent Grade	Truck Hill-Climbing Speed (mph)		
	100 lb/hp	200 lb/hp	300 lb/hp
3	51	37	28
5	44	26	19
7	36	20	14

Source: Estimated from figures presented in the *Highway Capacity Manual* (TRB, 1985)

Exhibit 2. Maximum Acceleration from Standing Start

Vehicle Type	Weight-to-Power Ratio (lb/hp)	Typical Maximum Acceleration Rate on Level Road (ft/sec^2)				
		0 to 10 mph	0 to 20 mph	0 to 30 mph	0 to 40 mph	0 to 50 mph
Passenger Car	25	9.3	8.9	8.5	8.2	7.8
	30	7.8	7.5	7.2	6.8	6.5
	35	6.8	6.5	6.2	5.9	5.5
Tractor-semitrailer	100	2.9	2.3	2.2	2.0	1.6
	200	1.8	1.6	1.5	1.2	1.0
	300	1.3	1.3	1.2	1.1	0.6
	400	1.3	1.2	1.1	0.7	--

Passenger car acceleration rates based on performance equations on p. 6 of A.D. St. John and D.R. Kobett, *Grade Effects on Traffic Flow Stability and Capacity*, National Cooperative Highway Research Program Report 185 (Washington D.C.: Transportation Research Board, 1978).

Truck acceleration based on data from T.D. Hutton, "Acceleration Performance of Highway Diesel Trucks," Paper No. 70664 (Society of Automotive Engineers, 1970).

Source: Institute of Traffic Engineers; *Traffic Engineering Handbook*; Prentice Hall, Englewood Cliffs NJ; 1992.

Exhibit 3. Maximum Acceleration for 10-mph Increments

Vehicle Type	Weight-to-Power Ratio (lb/hp)	Typical Maximum Acceleration Rate on Level Road (ft/sec^2)			
		20 to 30 mph	30 to 40 mph	40 to 50 mph	50 to 60 mph
Passenger car	25	7.8	7.1	6.3	5.6
	30	6.5	5.8	5.2	4.5
	35	5.6	5.0	4.4	3.8
Tractor-semitrailer	100	2.1	1.5	1.0	0.6
	200	1.3	0.8	0.5	0.4
	300	1.0	0.6	0.3	--
	400	0.9	0.4	--	--

Based on the same data as Exhibit 2

Source: Institute of Traffic Engineers; *Traffic Engineering Handbook*; Prentice Hall, Englewood Cliffs NJ; 1992.

Other factors being equal, increased truck length also makes merging, weaving, and changing lanes more difficult, although such effects are very difficult to quantify.

In many states, trucks are restricted to the rightmost lanes and are prohibited from using the leftmost or median passing lanes except where necessitated by left-hand exits and merges. The effect of this regulation is to increase the density of trucks in the rightmost lanes. Where there are large volumes of traffic entering or exiting the freeway, trucks tend to dwell in the second lane to avoid frequent lane and speed changes caused by merging traffic. This creates a barrier to merging traffic. Research on this effect is limited and inconclusive, but indicates that, when the freeways are saturated during peak periods, trucks and automobiles stay in the acceleration lanes longer than normal, and many merges are forced (Grenzeback, 1990).

In a study conducted for the Association of American Railroads, Mingo (1991) found that tractor-trailers cause significantly more lane changes per mile of operation than do passenger cars on a per-vehicle basis. The study used the INTRAS traffic simulation model, which simulates the behavior of individual vehicles and includes the capability of counting the total number of lane changes.

1.3 Capacity Effects and Passenger Car Equivalents

The *Highway Capacity Manual* presents detailed tables of PCE values on freeways for light (100 lb/hp), medium (200 lb/hp), and heavy (300 lb/hp) trucks as a function of the steepness and length of grade, the percentage of trucks in the traffic stream, and number of lanes. Exhibit 4 shows PCE values by type of truck, steepness of grade, and length of grade for four-lane freeways with 6 percent trucks. PCE values increase for steeper and longer grades, since as heavy vehicles travel up a grade, their impact becomes more severe as their speeds decrease. There are no differences between medium and heavy trucks for grades of one-quarter mile or less. However, the differences are significant for exceptionally long and steep grades.

In a study for the Association of American Railroads (AAR), Mingo (1994) used FRESIM, a microscopic freeway simulation model in which individual vehicles are simulated on a second-by-second basis, to develop PCE factors for several different types of trucks: a 28-foot single-unit truck, a 65-foot tractor-semitrailer with a medium load, a 65-foot tractor-semitrailer with a full load, a 70-foot double-bottom trailer truck, and a 110-foot longer combination truck. The methodology involved making a large number of FRESIM runs for each of five typical freeway sections (urban, rural on flat terrain, rural on rolling

Exhibit 4. Passenger Car Equivalents on Freeways by Truck Type and Grade

Grade (%)	Length of Grade (mi)	Passenger-Car Equivalent					
		Light Truck (100 lb/hp)		Medium Truck (200 lb/hp)		Heavy Truck (300 lb/hp)	
		4-Lane Freeway	6-8 Lane Freeway	4-Lane Freeway	6-8 Lane Freeway	4-Lane Freeway	6-8 Lane Freeway
2	0 - 0.25	2	2	3	3	3	3
	≥ 1.50	2	2	5	4	6	5
4	0 - 0.25	3	3	4	4	4	4
	≥ 1.50	4	4	8	6	9	8
6	0 - 0.25	4	4	6	5	6	5
	≥ 1.50	6	5	9	8	18	14

Source: *Highway Capacity Manual* (TRB, 1985) terrain, and two rural on mountainous terrain), covering variations in traffic volumes and vehicle mix. Regression analysis was then used to estimate the relative impacts on travel time and on capacities for different types of vehicles. Mingo recommends PCE values based on travel times as the most appropriate for general application, since truck travel occurs much less frequently during saturated-flow conditions than during moderate-to-heavy flow conditions. Exhibit 5 presents the travel-time-based PCE values developed by Mingo for the five freeway sections and five truck types. The "general freeway" truck PCEs recommended in the Highway Capacity Manual are 1.7 for flat terrain, 4.0 for rolling terrain, and 8.0 for mountainous terrain.

The PCE values developed by Mingo for 110-foot combinations are considerably greater than his PCE values for fully-loaded tractor-semitrailers and 70-foot double bottoms. Much of the difference could be due to the poor acceleration characteristics assumed by Mingo for long combinations. FRESIM allows the model user to define performance characteristics for each of the vehicle types simulated. For maximum acceleration, a key characteristic affecting PCE values, Mingo used FRESIM default values for four of the truck types analyzed and developed special inputs for long combinations to reflect lower power-to-weight ratios. For example, at a speed of 80 feet per second, the maximum acceleration rate assumed by Mingo for long combinations was 0.033 ft/sec^2, as compared with 0.325 ft/sec^2 for fully-loaded tractor-semitrailers and 0.141 ft/sec^2 for 70-foot double bottoms. If it is instead assumed that the power of long combination engines is increased to compensate for their greater weights, the PCE values for these trucks would be much closer to those of double bottoms.

The PCE values of trucks are affected by both length and weight. However, no studies have been found that separate these two effects.

In considering the net effects of changes in truck size and weight limits on capacity and level of service, it is important to consider not only the effects of changes in limits on PCE values for trucks, but also how the changes in limits affect truck volumes on congested roads. Generally, these two effects operate in opposite directions; e.g., increases in truck weight limits will increase PCE values for fully-loaded trucks, but will decrease truck volumes.

In assessing the role of heavy trucks in causing congestion-related delays to other vehicles, the types of highways used and time of travel by these trucks are important considerations. Heavy trucks traveling on congested highways during peak periods can delay other vehicles. Conversely, heavy trucks traveling on low-volume multilane roads during off-peak periods have little if any effect on delays to other vehicles. According to *Highway Statistics*, in 1992 combinations accounted for 4.4 percent of vehicle miles of travel (VMT)

Exhibit 5. Passenger Car Equivalents for Different Truck Types on Typical Freeway Sections from AAR Study

	Urban	Rural -- Flat	Rural -- Rolling	Mountainous 1	Mountainous 2
Single Unit Truck	1.887	1.189	1.402	1.346	1.832
Tractor-Semi with Medium Load	3.349	2.516	2.760	3.001	3.361
Tractor-Semi with Full Load	4.844	3.146	3.803	4.262	4.613
Double Bottom	6.881	5.130	6.346	7.302	13.765
Long Combination	10.890	10.080	12.115	17.093	70.715

Source: Mingo and Zhuang; *Passenger Car Equivalents of Larger Trucks Derived from Use of FRESIM Model*; 1994 on the nation's highways. However, they accounted for 15.3 percent of VMT on rural Interstates and 5.7 of VMT on urban Interstates.

On rural Interstates, heavy trucks travel a lower-than-average portion of their miles on the most congested highways. Approximately 32.2 percent of all rural interstate highway traffic travels on roads with the highest volume-to-capacity (v/c) ratios (peak period v/c ratios equal to 0.65 or more). However, only 27.8 percent of truck travel is on roads with peak period v/c ratios greater than 0.65 (Highway Performance Monitoring System, 1989 Data Tape). The category "trucks" in the HPMS data actually includes all trucks and buses with more than four tires. In the 1989 data tape, HPMS section data records do not contain a breakdown by type of truck, so any attempt to analyze the impact of truck size and weight regulations (which generally will impact only the largest or heaviest of trucks) could be impaired by this lack of distinction in the data. The 1993 HPMS data tape will provide separate estimates of truck percentages for single-unit trucks and combinations.

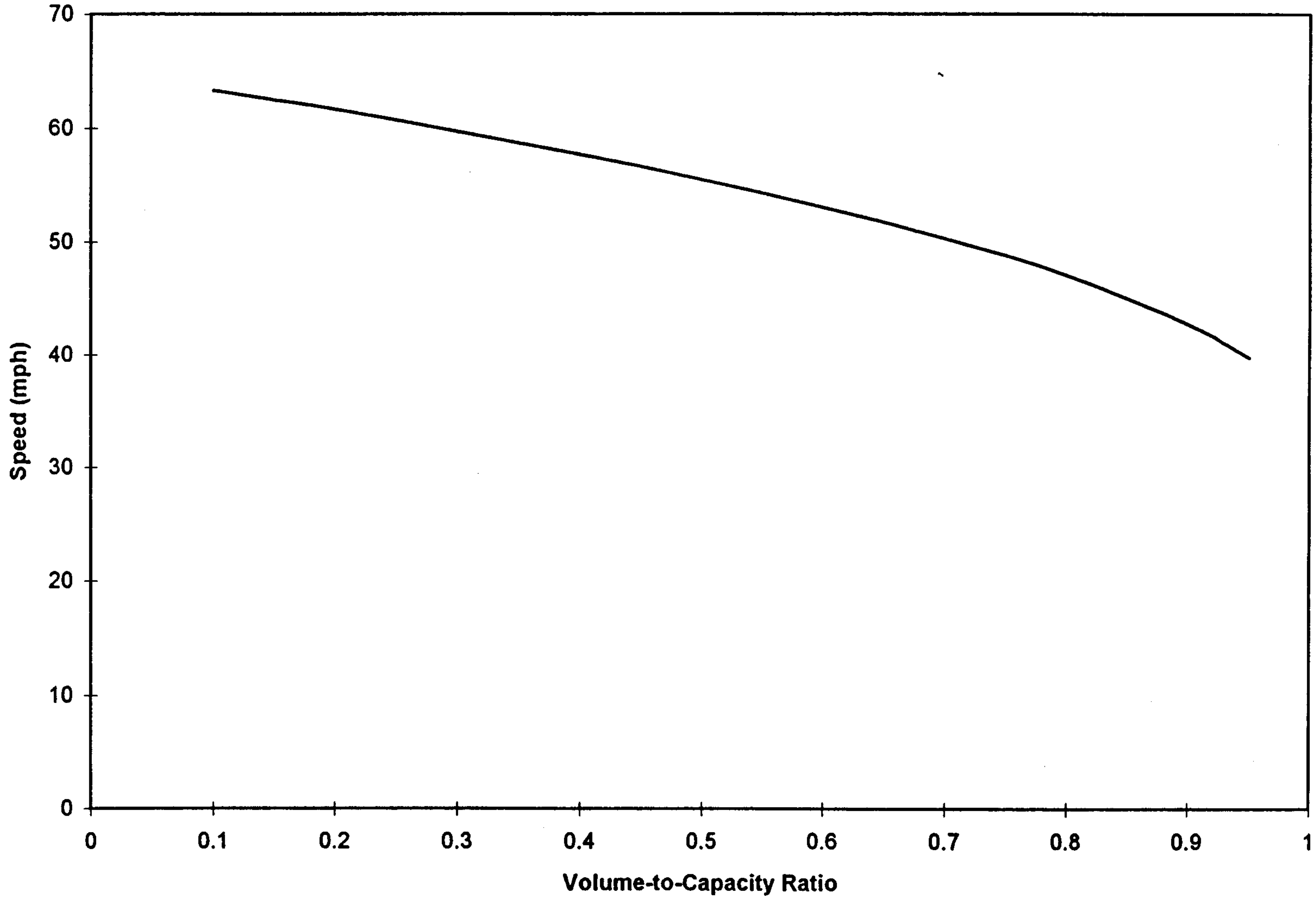
Regarding urban freeways, Grenzeback (1990) notes that as a general pattern, highly congested freeway segments tend to have slightly lower truck percentages than moderately congested freeway segments. Specifically, he estimated that thirty percent of freeway segments in Los Angeles, twenty percent of freeway segments in San Francisco, and ten percent of freeway segments in San Diego are highly congested (with stop-and-go traffic averaging less than 35 miles per hour). Large truck volumes accounted for 3.5 percent of total traffic on these segments, while large truck volumes on moderately congested freeway segments accounted for 4.2 percent of total traffic.

1.4 Marginal Costs

In an analysis for the Association of American Railroads (AAR) of Travel-Time Costs of Increased Truck Travel on Rural Interstate Highways, Mingo estimated the marginal cost to other vehicles associated with an additional mile of travel of a typical combination truck. On average, Mingo found that removing one truck from the rural Interstate system during peak travel hours would save an average of 79 cents per mile of travel in time costs -- 17 cents on flat freeways, $1.21 on rolling freeways, and $2.50 on mountainous freeways. He also found that removing one randomly selected truck from the rural Interstate system would save an average of 31 cents per mile of travel in time costs -- 7.5 cents on flat freeways, 46 cents on rolling freeways, and $1.00 on mountainous freeways.

Mingo's estimates were developed using an assumed value of time of $15 per vehicle hour and the speed versus volume-to-capacity relationship shown in Exhibit 6. This relationship, which is based on the Greenshield's traffic-flow

Exhibit 6. Speed Flow Relationships from AAR Study



equation, is similar in shape to speed-volume relationships presented in the 1985 *Highway Capacity Manual*. However, recent research has resulted in very substantial revisions to these relationships. Exhibit 7 shows the speed-flow relationships for multilane highways from the 1985 *Highway Capacity Manual*, and from a 1992 revision to the manual. The new relationships keep speeds constant until 75 percent of capacity, and drop only 5 miles per hour between 75 and 100 percent of capacity. The old relationships were parabolic, with speeds decreasing over the entire range of flows. For a freeway with a free-flow speed of 60 miles per hour, speeds dropped to about 50 miles per hour at 90 percent of capacity and to about 30 miles per hour at 100 percent of capacity. The practical implications of these differences are of great importance in calculating marginal congestion costs. Using a PCE value of 4.0 for trucks and $15 per vehicle hour as the value of time, the added cost per truck mile using the speed versus volume-to-capacity ratio curve shown in Exhibit 4 is 23 cents per truck mile at a v/c ratio of 0.5. However, using the 1992 revisions to the *Highway Capacity Manual*, the marginal time delay cost would be less than one cent per truck mile at this v/c ratio. Under the same assumptions, the marginal cost is about 80 cents per truck mile at a v/c ratio of 0.8 versus roughly 20 cents per truck mile using the 1992 revisions to the *Highway Capacity Manual*.

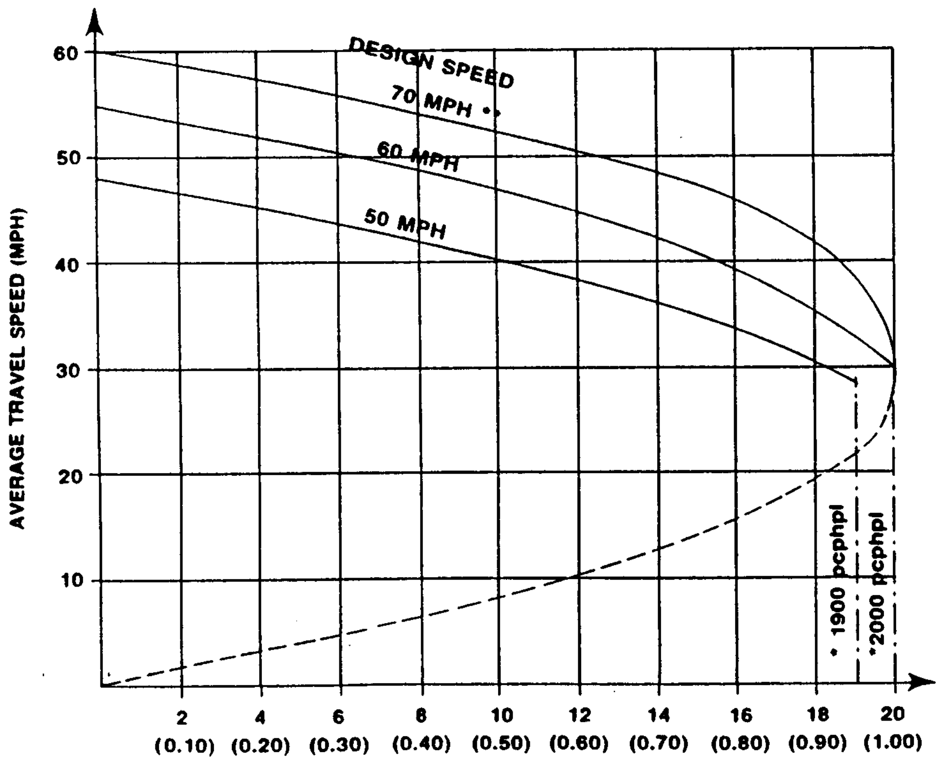
1.5 Signalized Intersections

The duration of the yellow phase should provide adequate time for vehicles not stopping at a traffic signal to clear the intersection. According to Hutchinson (1988), typical clearance times at signalized intersections are generally inadequate for existing combination vehicles. Increasing the length of combinations would increase the time required for these vehicles to pass through a signalized intersection and exacerbate this problem. TRB Special Report 227 (1990) estimated that 80- to 85-foot doubles would require at least 0.5 to 0.6 seconds of additional clearance time relative to the existing five-axle twins or tractor-semitrailers to safely cross and clear the intersection.

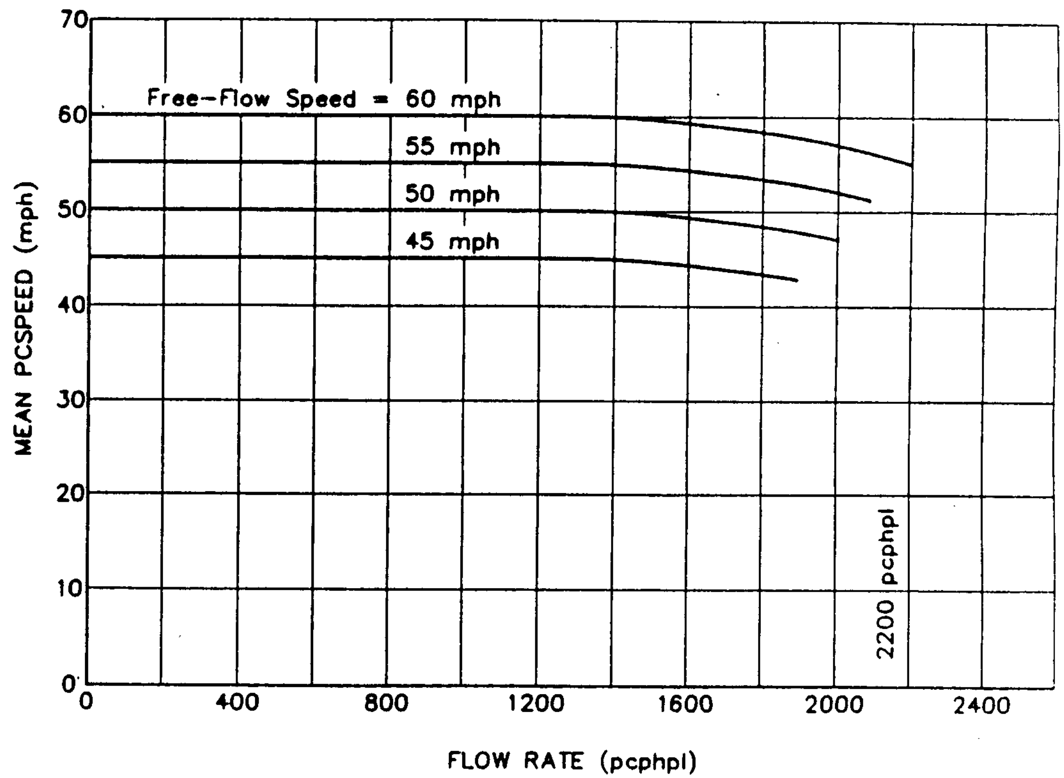
1.6 Longitudinal Barriers

Longitudinal barriers such as guardrails, bridgerails, and median barriers are designed to reduce the severity of accidents by restraining and redirecting vehicles upon impact. Most existing longitudinal barriers are designed for passenger vehicles up to 4,500 pounds and center-of-gravity heights of 24 inches (Hirsch 1986). Although designers have developed barriers for restraining and redirecting trucks, such barriers are not widely used (TRB Special Report 225; 1990). Thus, increasing truck sizes and weights is not expected to significantly affect costs for longitudinal barriers.

Exhibit 7. Speed-Flow Relationships for Multilane Highways



1985 Highway Capacity Manual



1992 Revisions

1.7 Sign Placement

The Manual on Uniform Traffic Control Devices (MUTCD; 1988) provides criteria for the placement of warning signs in advance of hazardous locations. These criteria take into account the time required for driver judgment about what action to take and the time required for the action itself (for example, stopping or decelerating to a lower speed). Harwood (1990) found that MUTCD criteria for sign placement should be revised to account for the fact that trucks require longer stopping distances than passenger vehicles. To the extent that increases in vehicle weights may reduce the stopping distance performance of trucks (an issue discussed in Working Paper No. 5), further revisions in these criteria might be desirable. However, Harwood notes that his recommended changes in advance warning sign placement criteria would not be necessary if "trucks with anti-lock braking systems come into nearly universal use." Thus, requiring the use of anti-lock brakes on trucks carrying increased weights would obviate the need for changes in sign placement criteria to accommodate these trucks.

2.0 Knowledge Gaps and Research Needs

In general, increasing the weight or length of a truck without making other compensating changes (such as a more powerful engine) will worsen the performance of the truck from a traffic operations perspective. However, changing size and weight limits can also reduce the total volume of truck traffic on highways, so that the net effect of increased size and weight on traffic operations could be positive or negative. Research is needed to determine the incremental effects of changes in size and weight, so that it becomes possible to analyze how specific changes in regulations will affect congestion and traffic operations.

Most past research on passenger car equivalents for heavy vehicles has focused on developing information useful to highway planners and traffic operations analysts for designing highways and traffic operating systems. Little emphasis was placed on developing specific information about how PCE values vary with truck weights, truck lengths, and other truck characteristics that might be affected by changes in truck size and weight regulations.

To estimate the impacts of trucks on congestion, better information is needed on the volume of truck traffic on different types of facilities, distributed by configuration, operating weight, and time of day.

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