# Operational Effects of Larger Trucks on Rural Roadways

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Ability of various truck configurations to negotiate rural roads with restrictive geometry was examined in addition to effects of such trucks on traffic operations and safety. Truck sizes included truck-tractor semitrailers with trailer lengths of 40, 45, and 48 ft (i.e., semi-40, semi-45, and semi-48) and twin-trailer combinations with 28-ft trailers (i.e., twins or double 28). Test sites consisted of approximately 60 mi of rural, two-lane roads in New Jersey and California with a variety of lane widths, shoulder widths, and horizontal and vertical alignment. Field testing involved following control trucks of each truck type along the selected routes. Photographic and radar equipment were used in a data collection caravan to measure the effects of the trucks on oncoming vehicles in terms of speed changes and lateral placement changes. Statistical testing was used to compare operational differences between various truck types for specific geometric conditions. Results showed that semi-48 and twins caused some changes in operation of oncoming vehicles, particularly on narrow roadways. However, careful driving by drivers of larger trucks may have partially compensated for operational differences in oncoming vehicles between truck types. Overall, truck driving behavior and site differences had more of an effect on vehicle operations than the effects of the different truck types. Potential safety problems as evidenced by extreme maneuvers were observed for a few oncoming motorists in reaction to the twins and longer tractor semitrailers.

The Surface Transportation Assistance Act of 1982 (1982 STAA) requires that states allow the operation of wider and longer trucks on the Interstate and other designated federal-aid highways, termed the National Network. In terms of trailer widths on the National Network, states may not impose width limits more or less than 102 in. (except for Hawaii, which has a 108-in. maximum). Before 1982, a maximum truck width of 96 in. was commonly used by most states. The 1982 STAA also provided that states allow semitrailers of at least 48 ft operating in a tractor-semitrailer combination and twin 28-ft semitrailers operating with a tractor on the National Network. Many states now allow semitrailers of 53 ft on the National Network.

Serious questions have been raised regarding the safety of these larger trucks and the ability of various portions of the highway system to safely handle such larger trucks. According to STAA, highways on which larger trucks are allowed to operate should be carefully selected to avoid unnecessary hazards to other road users. In order to perform such a selection, the effect of the operation of larger trucks on safety and traffic operations must be evaluated.

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Turnpike and Interstate systems that exist today have generally been built with high geometric standards. However, the federal-aid primary system and secondary system in many instances includes lower geometric designs, which may preclude the safe operation of large trucks. Because of higher speeds on rural highways, potential for severe truck accidents is increased on roads with narrow lanes and shoulders, sharp curves on steep grades, poor sight distance, and hazardous roadside conditions. Existence of such restrictive geometry may impact safety and limit operations of the larger trucks specified in the 1982 STAA. Therefore, the impacts of larger truck operations on restrictive geometry must be evaluated to provide insights relative to appropriate geometric criteria in the truck route selection process for various types of larger trucks.

Ability of various truck configurations to negotiate rural roads with restrictive geometry was determined in addition to effects of such trucks on the traffic operations and safety of such roads. Truck sizes included truck-tractor semitrailers with trailer lengths of 40, 45, and 48 ft and trailer widths of 96 and 102 in. Twin-trailer combinations with 28-ft trailers were also included. Truck sizes were studied on arterials and collector routes designed to lower standards and not on arterials and freeways.

A 2-year FHWA study dealing with truck effects on rural roads and at urban intersections was used (*1*). Results dealing with urban intersections were reported previously by Hummer et al. (*2*). However, operational field testing of various truck sizes at selected rural sites considered to have problem geometrics is discussed. An analysis was conducted of operational field data to determine the effect of larger trucks on the safety and operations relative to oncoming vehicles in the traffic stream. Information also was gained on geometric conditions that may pose a problem for specific truck types.

## BACKGROUND

### Accident Studies

Of the many research studies conducted in recent years on large truck safety and operations, several have compared accident rates of various truck types. A 1988 study by Jovanis et al. (*3*) found that twins (i.e., tractors with two 28-ft trailers) had a significantly lower accident rate than semis (tractor semitrailers) on Interstate, state, and local roads. The study was based on a matched pair analysis of 3 years of accident and exposure. Stein and Jones (*4*) found twins to be overinvolved in crashes compared with semis on the basis of data collected on two Interstate highways in Washington state. Using California data, Graf and Archuleta (*5*) concluded that twins have higher accident involvement rates than semis on rural roads, but a lower involvement rate on urban streets. On the basis of 5 years of fatal truck accident and exposure data for heavy trucks (greater than 10,000 lb), Campbell et al. (*6*) found that twins have a 10 percent higher fatal accident rate nationwide than semitrailers after adjusting for differences in travel by road class, time of day, and area of truck travel.

A 1981 study by Glennon (*7*) used matched-pair analysis of freight carriers in Pennsylvania (1976 to 1980 data) and found no significant difference in accident rate between twins and semitrailers. Similarly, studies by Chira-Chavala and O'Day (*8*) and by Yoo et al. (*9*) also found little or no difference in accident rates between twins and semitrailers. On the basis of a synthesis of prior studies, a 1986 TRB study found twins to be slightly overinvolved in truck crashes compared with semitrailers, but projected a reduction in truck travel from the greater carrying capacity of twins that would offset any accident increase (*10,11*).

All of these studies attempted to compare accident rates only between twins and semitrailers, but not between trailer width (96 versus 102 in.) or length of trailers (e.g., 45 versus 48 ft) probably because of the difficulty in obtaining trailer size data for truck accidents and exposure. Several, but not all, of the studies appropriately controlled for highway type, time of day, or driver characteristics that can have a considerable influence on the results.

### Operational Studies

A 1982 field study by Seguin et al. (*12*) analyzed the effects of truck sizes on certain traffic situations. Methodology involved photographing lateral placement of oncoming vehicles and measuring their speeds from a van following a staged truck that could be expanded to widths of 96, 102, 108, and 114 in. Results suggest that vehicles passing any large truck (in the same direction) tend to move away from the center of the lane. Increased widths caused drivers who wished to pass to follow the truck at a greater distance to allow adequate sight distance for passing. However, no increases in shoulder encroachments or acceptances of smaller gaps were found for passers of wider trucks.

A 1981 study by Hanscom (*13*) included the effects of truck size, configuration, and weight on traffic and trucks for several types of roadway geometrics. Study sites included upgrades, downgrades, curves with grades, a freeway ramp, a freeway merge, and an intersection. Despite numerous operational differences associated with truck size and weight, the observed effects were weak. Typical truck differences found were reduced speeds, higher deviations from traffic mean speeds, and higher clearances of following vehicles, all exhibited by loaded and double-trailer rigs (by comparison with empties and singles, respectively). Negligible operational effects were found to be associated with truck length. Adverse safety effects were most pronounced on upgrades, whereas certain safer behavior was noted for heavier trucks on downgrades. The analysis demonstrated that a maximum of only 37 percent of truck operational effects were explainable by truck size and weight (*13*).

Numerous other studies have been conducted dealing with a variety of truck safety and operational issues such as truck offtracking (*14–16*), performance on curves and ramps (*17,18*), operations of oversized loads (*19*), critical overturning speeds (*20,21*), adequacy of current AASHTO design standards to accommodate current truck sizes (*22*), and others. One of the key unanswered issues still involves the effects of truck sizes and configurations on various rural road situations and types of roads where such trucks should be permitted.

## DATA COLLECTION

### Candidate Study Conditions

Conditions selected included tangent and curve sections of two-lane rural roads, including various roadway widths. Oversized trucks operating on such roads could run off the road or encroach on lanes of high-speed opposing traffic. Numerous combinations of roadway geometry and truck size were examined on the basis of accident potential, traffic flow problems, and available operational parameters to support safety analyses.

Truck types selected include the baseline 40-ft semitrailer, about which much is known operationally; pre-1982 maximum size 45-ft semitrailer; post-1982 semitrailer of 48 ft; and 28-ft twin-trailer truck. Many 48-ft semitrailers have rear axles that may be moved forward or backward relative to the cab. Better load-bearing capability is achieved when the axles are back. Because the 48-ft semitrailer is generally more maneuverable with axles forward, the vehicle was studied with the rear axles positioned forward and backward as far as possible relative to the truck cab.

Measures of effectiveness (MOEs) examined on the rural two-lane roads were all measures of driver behavior while passing trucks from the opposing direction. These MOEs included lateral placement of random oncoming vehicles with respect to the truck's rear tires and changes in lateral placement and speed of opposing vehicles as they approached the truck. Independent variables included various roadway geometric and traffic parameters (tangent or curve, degree of curve, number of curves per mile, speed limit, etc.), opposing vehicle type and size, and truck size.

Use of random oncoming vehicles was considered to provide a representative sample of drivers and vehicles in the traffic stream on the selected routes. This method was used because of the large sample of observations that would probably cancel biases related to driver age, gender, etc. Use of random vehicles in the traffic stream is a technique used by Seguin et al. (*12*) and Parker (*19*) in their operational studies of trucks and oversized loads, respectively.

### Data Collection Methods

Collection of the rural two-lane data involved a caravan of three control vehicles traveling along the road encountering free-flow oncoming vehicles, as shown in Figure 1. A lead car was positioned at the head of the caravan. An observer in the lead car informed the other caravan vehicles via radio that a free-flow oncoming vehicle was approaching for study,

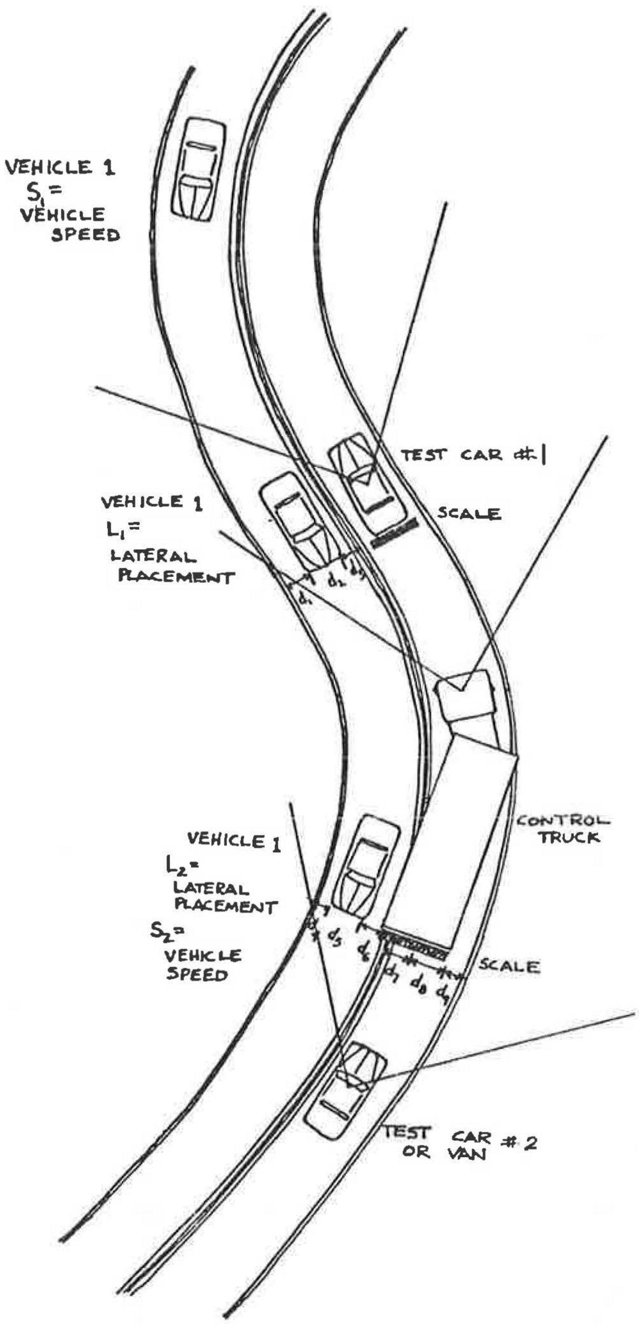


**FIGURE 1 Overview of rural data collection.**

assigned the vehicle an identification number, recorded the oncoming vehicle's speed by use of a moving radar meter, and noted the odometer reading (for later use in matching MOEs to roadway geometric data). The control truck of known size traveled approximately 0.1 mi behind the lead car. An observer in the truck photographed the oncoming vehicle when directly beside the lead car. A scaled board attached to the rear bumper of the lead car provided a reference so that a slide of the photograph could be used later to measure the oncoming vehicle's lateral placement.

The trail car of the caravan traveled immediately behind the control truck. An observer in the trail car recorded the speed of the oncoming vehicle while passing the control truck using the moving radar device and another observer photographed the oncoming vehicle when directly beside the rear of the truck. Again, lateral placement of the oncoming vehicle could be determined because a scaled board was also attached to the rear of the truck. Odometer readings were also recorded at that point for verification of the match to roadway geometric data.

Rural two-lane data were collected over predesignated routes in California and New Jersey for a variety of roadway geometrics, including narrow and wide lanes and shoulders, curves and tangents, and under various traffic volume conditions. Data were collected during daylight hours with dry pavement conditions. The data collection methodology proved accurate and efficient. Speeds were recorded to the nearest mile per hour and lateral placements within approximately 0.2 ft.

## RESULTS

Data collection procedures resulted in the collection of speed and lateral placement data for samples of vehicles opposing each type of control truck (i.e., semi-40, semi-45, semi-48, and double-28) on two-lane rural roads. Each data point was later matched to a detailed set of information on the roadway geometrics at that point. Data analysis mainly involved separating effects of different geometric variables from the effects of truck size so that an accurate assessment could be obtained of differences between truck sizes for various rural conditions.

## MOEs

Information recorded on the operation of each opposing vehicle in the data set included (a) speed at the lead car, (b) speed at the truck, (c) lateral placement at the car (in relation to the centerline and edgeline of the road), and (d) lateral placement at the truck. Other MOEs created from these data included the speed change of opposing vehicle (speed at the lead car minus speed at the truck), lateral placement change of the opposing vehicle (lateral placement at the lead car minus the lateral placement at truck), and clearance between the truck and opposing vehicle. Several discrete (yes or no) variables were also analyzed, such as whether a vehicle slowed (from lead car to truck) more than 5 mph and whether a vehicle was on or to the right of the edgeline when beside the truck.

### Roadway Variables Collected

Different geometric and traffic variables were collected for rural, two-lane conditions, including lane and shoulder width, degree of curve (or tangent), shoulder type (paved, gravel, or turf), speed limit, and intersection presence (with type of control). Data for most of the traffic and roadway variables were collected from more than one source for checking purposes, such as from field observations, photologs of the site, aerial photographs, and state department of transportation records. For each recorded opposing vehicle event, information was also recorded on the size of control truck (configuration, trailer length and width, and axle placement) and on the type of opposing vehicle (small car, medium car, large car, pickup, van, station wagon, bus, small truck, or semitrailer).

Data for this study were desired only for rural roadways with speed limits of 45 and 55 mph under free-flow conditions (i.e., not within the influence of traffic signals). Thus, samples were excluded near signalized intersections, in towns and built-up areas, or where the speed limit was 40 mph or less. Several variables were collected but not used in the analysis, including shoulder type, because all shoulders in the sample sections were paved. The speed limit variable was not used in the analysis because speed was found to be strongly intercorrelated with other roadway variables used in the analysis.

Categories of several variables were grouped as a result of the sample sizes. Three categories remained with respect to curves and tangents:

- Lead car and truck on tangent,
- Lead car and truck on inside curve, and
- Lead car and truck on outside curve.

Samples were excluded for all other curve combinations (i.e., car on curve and truck on tangent for the same oncoming vehicle) because *t*-tests showed that the change in MOE for these conditions may be caused by geometric difference between curves and tangents and not by the presence of the truck. Also, sample sizes were small for these mixed combinations.

**Sample Sizes**

After eliminating the data collected near intersections, on segments with speed limits of 40 mph or less, and on certain curve combinations, the remaining sample consisted of 3,330 observations with dry pavement conditions. A summary is presented in Table 1 of the sample sizes by truck type for certain geometric conditions. Overall, the largest sample was collected for the semi-40 (868 observations), followed by the semi-45 (756 observations), and semi-48 with axles back (703 observations), double-28 (648 observations), and semi-48 with axles forward (355 observations).

**Analysis Issues**

Generally, the key issues addressed during analysis of the rural data included the following:

1. What roadway geometrics affect vehicle operations (i.e., vehicle speed and lateral placement) relative to large trucks on rural two-lane roads?
2. Were there differences in driving behavior between drivers of various truck sizes that could partially account for differences in the operation of oncoming traffic?
3. Do differences in MOEs exist between the semi-40, semi-45, semi-48 with axles back, semi-48 with axles up, and double-28, and if so, for what geometric conditions?
4. What were the most extreme reactions to the different control trucks by oncoming traffic and were any trends revealed?

A secondary purpose of the first issue was to help group data for analysis for the second and third issues. The fourth issue was addressed even though relatively few such events were expected to occur. Nonetheless, the number of extreme vehicle reactions (i.e., near-miss accidents) may be indicative of serious safety concerns for various truck types. For the third issue, more specific subquestions are addressed involving comparisons between pairs of truck types and sizes (e.g., comparing operations of a semi-40 versus semi-48).

*Issue 1: Roadway Geometrics That Affect Operations Relative to Large Trucks on Two-Lane, Rural Roads*

Lane width, shoulder width, presence of curvature, and to a lesser extent degree of curvature, all affect opposing vehicle operation relative to large trucks on two-lane, rural roads for the range of conditions tested.

One-way analysis of variance (ANOVA) tests were performed on roadway geometric variables using continuous MOEs for oncoming vehicles (a) speed change, (b) lateral placement at the trucks, and (c) lateral placement change. Results indicate that each variable tested has statistically significant changes for at least one MOE. Mean MOE values for some variable level show that there were generally only marginal changes in the means that were probably not operationally important. Thus, discrete MOEs aimed at identifying large operational changes were examined for lane width, shoulder width, and curve presence for the semi-48 with axles back. Results indicate that for the conditions tested, lane width was not an important factor with speed change MOEs, but that greater lane widths (i.e., 12- and 13-ft lanes) allow some opposing vehicles to move farther right when confronting a truck.

Shoulder width was a significant variable for both speed and lateral placement MOEs for the conditions tested. Speeds

TABLE 1 SUMMARY OF RURAL SAMPLE SIZES FOR VARIOUS TRUCK TYPES AND GEOMETRIC CONDITIONS

| | Lane Width = 10 and 11 ft | | | | Lane Width = 12 and 13 ft | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Shoulder Width = 0 to 4 ft | | Shoulder Width ≥ 4 ft | | Shoulder Width = 0 to 4 ft | | Shoulder Width ≥ 4 ft | | |
| Truck Type | Tangent | Curve | Tangent | Curve | Tangent | Curve | Tangent | Curve | Total |
| Semi–40 | 135 | 50 | 141 | 64 | 128 | 64 | 141 | 145 | 868 |
| Semi–45 | 134 | 57 | 169 | 52 | 121 | 52 | 129 | 42 | 756 |
| Semi–48 (back) | 112 | 42 | 173 | 46 | 121 | 45 | 103 | 61 | 703 |
| Semi–48 (forward) | 108 | 48 | 12 | 6 | 78 | 32 | 37 | 34 | 355 |
| Double–28 | 116 | 43 | 95 | 36 | 111 | 58 | 68 | 121 | 648 |
| Total | 605 | 240 | 590 | 204 | 559 | 251 | 478 | 403 | 3,330 |

of oncoming vehicles increased by a greater amount between the lead car and the truck for wider shoulders than for narrow or absent shoulder conditions. Speed change MOE results showed that more vehicles increased speed between the lead car and the truck than decreased speed. This finding was likely caused by the tendency of oncoming motorists to decrease speed before passing the truck and then accelerate back to a comfortable free-flow speed as they passed the truck. Shoulders less than 4 ft wide tended to result in fewer vehicles on or over the edgeline and in combination with 12- and 13-ft lane widths resulted in more vehicles making lateral placement changes of 1 ft or more.

Presence of curvature affected the change in lateral placement, whereas direction of curvature (inside or outside curve) was not important for the conditions tested. The strong effect of curve presence on the three MOEs was also found. In all but one case of lane and shoulder width combinations, presence of curvature caused a change in the operation of oncoming traffic.

Degree of curvature did not affect the change in lateral placement (controlling for curve presence) and resulted in generally large speed reductions only at degrees of curvature greater than 7°. Direction of curve (i.e., inside or outside as faced by the opposing vehicle) did not have a significant effect on speed and lateral placement changes on the basis of *t*-tests.

In light of these findings for the effects of geometrics, results of one-way ANOVA tests on other variables (such as opposing vehicle size), and reexamination of available sample sizes, the approach used for the remaining analyses would include controls for lane width (10- or 11-ft widths versus 12- or 13-ft widths), shoulder width (shoulders less than 4 ft wide versus shoulders greater than 4 ft wide), and presence of curvature (yes versus no). The state variable (New Jersey or California sites) was controlled whenever appropriate. Finally, opposing vehicle type was controlled in the analyses involving lateral placement, on the basis of the one-way ANOVA tests.

### *Issue 2: Differences in Driving Behavior That Could Partially Account for Differences in Operation*

Significant differences were found in the lateral placement of some of the control trucks in the lane that could have had an effect on the operation of oncoming vehicles. Qualitative observation of the various control trucks in the field revealed that control-truck drivers made efforts to operate each truck type safely. For example, in operating the double-28 on narrow winding roads the driver was able to keep the vehicle within the lane with rare encroachments over the edgeline or centerline. However, the semi-48 with axles back had to be driven more cautiously on the narrow roads because of greater offtracking of the trailer when driving around curves. Thus, the driver often slowed the longer semitrailer considerably before approaching some of the curves. In some cases of curves to the left, on narrow lanes, for example, the driver of the semi-48 (with axles back) would encroach onto the right shoulder with the tractor to prevent the rear trailer from encroaching the centerline. The semi-40 and semi-45 had little or no problem in normal driving on most of the routes.

Because qualitative observations suggested that the driver had to exercise added care with certain truck types, data were analyzed to see the extent of differences between truck operations. Comparisons of truck types were made in terms of mean distances of the rear of the control truck from the centerline for instances when oncoming vehicles were directly beside the truck. This analysis was conducted only for more geometrically restrictive roadways (i.e., curve sections with lane widths of 10 or 11 ft and shoulders of 0 to 4 ft) because those were considered to be the most critical situations. Average distances of the control trucks to the centerline for these situations were

- Semi-40—2.11 ft,
- Semi-45—2.04 ft,
- Semi-48 with axles back—2.06 ft,
- Semi-48 with axles forward—1.84 ft, and
- Double-28—1.71 ft.

Even though results from offtracking models (*1*) show that the semi-48 offtracks more with axles back than with axles forward, the driver more than compensated for this because the semi-48 with axles back was generally farther from the centerline than the semi-48 with axles forward. In fact, the semi-40, semi-45, and semi-48 with axles back were each positioned about the same average distance (2.04 to 2.11 ft from the centerline) as they passed oncoming vehicles. The semi-48 with axles forward and double-28 were driven closer to the centerline, at 1.84 and 1.71 ft, respectively. Statistical *t*-tests were used to compare the means for each truck pair and to verify these differences, as presented in Table 2. Except for the comparison of the semi-48 with axles forward versus axles back (significance of 0.058), the double-28 and semi-48 with axles forward were positioned significantly closer to the centerline than were the other truck types (0.05 level).

An analysis was also conducted of the average clearance between each type of control truck and oncoming vehicles, as presented in Table 3. Average clearances for the truck types on the restrictive geometry were as follows:

- Semi-40—5.48 ft,
- Semi-45—5.38 ft,
- Semi-48 with axles back—5.54 ft,
- Semi-48 with axles forward—5.00 ft, and
- Double-28—4.82 ft.

The *t*-tests were used to compare the means for pairs of trucks, which showed that the semi-48 with axles forward and double-28 had significantly different clearances (i.e., less clearance distances) than the other three truck types.

In summary, drivers of the semi-48 with axles back compensated for added offtracking by the way in which they drove the vehicle. As a result, oncoming traffic was exposed to similar lane placements by the semi-40, semi-45, and semi-48 with axles back, and by lane placements that were closer to the centerline when passing the double-28 and semi-48 with axles forward.

### *Issue 3a: Differences in MOEs Between Semi-40, Semi-45, Semi-48 with Axles Back, Semi-48 with Axles Forward, and Double-28*

Differences in MOEs were observed between some of the truck types for a few of the geometric conditions tested. How-

TABLE 2 COMPARISON OF MEAN TRUCK DISTANCE TO CENTERLINE FOR CONTROL TRUCKS FOR SITES WITH RESTRICTIVE GEOMETRY (*t*-TESTS)

| Truck Type Comparison | Mean Distance of truck to centerline (feet) | | Calculated t-value | Degrees of freedom | Two-tail proba-bility | Significance | |
|---|---|---|---|---|---|---|---|
| | First truck type | Second truck type | | | | .05 | .01 |
| Semi 40 vs. Semi 45 | 2.11 | 2.04 | 0.62 | 105 | 0.536 | No | No |
| Semi 40 vs. Semi 48 (back) | 2.11 | 2.06 | 0.38 | 92 | 0.706 | No | No |
| Semi 40 vs. Semi 48 (forward) | 2.11 | 1.84 | 2.48 | 96 | 0.015 | Yes | No |
| Semi 40 vs. Double | 2.11 | 1.71 | 3.14 | 91 | 0.002 | Yes | Yes |
| Semi 45 vs. Semi 48 (back) | 2.04 | 2.06 | 0.15 | 99 | 0.883 | No | No |
| Semi 45 vs. Semi 48 (forward) | 2.04 | 1.84 | 2.27 | 103 | 0.025 | Yes | No |
| Semi 45 vs. Double | 2.04 | 1.71 | 3.11 | 98 | 0.002 | Yes | Yes |
| Semi 48 (back) vs. (forward) | 2.06 | 1.84 | 1.92 | 90 | 0.058 | No | No |
| Semi 48 (back) vs. Double | 2.06 | 1.71 | 2.61 | 85 | 0.011 | Yes | No |
| Semi 48 (forward) vs. Double | 1.84 | 1.71 | 1.23 | 89 | 0.221 | No | No |

TABLE 3 COMPARISON BETWEEN TRUCK TYPES OF MEAN CLEARANCE BETWEEN CONTROL TRUCKS AND ONCOMING TRAFFIC FOR SITES WITH RESTRICTIVE GEOMETRY (*t*-TESTS)

| Truck Type Comparison | Mean clearance between control truck and on-coming traffic (feet) | | Calculated t-value | Degrees of freedom | Two-tail proba-bility | Significance | |
|---|---|---|---|---|---|---|---|
| | First truck type | Second truck type | | | | .05 | .01 |
| Semi 40 vs. Semi 45 | 5.48 | 5.38 | 0.43 | 105 | 0.667 | No | No |
| Semi 40 vs. Semi 48 (back) | 5.48 | 5.54 | 0.27 | 92 | 0.788 | No | No |
| Semi 40 vs. Semi 48 (forward) | 5.48 | 5.00 | 2.24 | 96 | 0.028 | Yes | No |
| Semi 40 vs. Double | 5.48 | 4.82 | 2.74 | 91 | 0.007 | Yes | Yes |
| Semi 45 vs. Semi 48 (back) | 5.38 | 5.54 | 0.72 | 99 | 0.474 | No | No |
| Semi 45 vs. Semi 48 (forward) | 5.38 | 5.00 | 1.86 | 103 | 0.065 | No | No |
| Semi 45 vs. Double | 5.38 | 4.82 | 2.45 | 98 | 0.016 | Yes | No |
| Semi 48 (back) vs. (forward) | 5.54 | 5.00 | 2.64 | 90 | 0.010 | Yes | Yes |
| Semi 48 (back) vs. Double | 5.54 | 4.82 | 3.08 | 85 | 0.003 | Yes | Yes |
| Semi 48 (forward) vs. Double | 5.00 | 4.82 | 0.86 | 89 | 0.392 | No | No |

ever, for a majority of the situations tested, no significant differences were found. A summary of results of the truck type comparisons is presented in Table 4 for lateral placement changes of 1 ft or more. The *Z*-test for proportions was used for three MOEs.

- Proportion of lateral placement change $\geq 1$ ft from the centerline (Table 4). Only oncoming cars were used in this comparison because prior analysis showed the insensitivity of oncoming trucks and buses to the control truck in terms of lateral placement.
- Proportion of oncoming vehicles (all types) that experience a speed reduction of 5 mph or more at the truck, compared with their speed while approaching the lead car.
- Proportion of oncoming cars that pass the control truck while on or over the edgeline.

TABLE 4 SUMMARY OF TRUCK COMPARISONS ON RURAL ROADS USING *Z*-TESTS FOR LATERAL PLACEMENT CHANGE OF ≥1 ft

| | Lane Width = 10 and 11 ft. | | | | Lane Width = 12 and 13 ft. | | | |
|---|---|---|---|---|---|---|---|---|
| | Shoulder Width = 0 to 4 ft. | | Shoulder Width > 4 ft. | | Shoulder Width = 0 to 4 ft. | | Shoulder Width > 4 ft. | |
| Comparison | Tangent | Curve | Tangent | Curve | Tangent | Curve | Tangent | Curve |
| Semi 40 vs. Semi 45 | ↑ | ↑ | ● | ● | ● | ● | ● | ● |
| Semi 40 vs. Semi 48 (back) | ● | ● | ● | ● | ↓ | ● | ● | ● |
| Semi 40 vs. Semi 48 (forward) | ● | ● | | | ● | ● | | |
| Semi 40 vs. Double | ↑ | ● | ● | ● | ● | ● | ● | ● |
| Semi 45 vs. Semi 48 (back) | ● | ● | ● | ↓ | ↓ | ● | ● | ● |
| Semi 45 vs. Semi 48 (forward) | ● | ● | | | ● | ● | | |
| Semi 45 vs. Double | ● | ● | ↓ | ● | ● | ● | ● | ● |
| Semi 48 (back) vs. (forward) | ● | ● | | | ↑ | ● | | |
| Semi 48 (back) vs. Double | ↑ | ● | ● | ● | ↑ | ● | ● | ● |
| Semi 48 (forward) vs. Double | ↑ | ● | | | ● | ● | | |

● = No significant difference in MOE.

↑ = Significant increase in MOE for second truck type (i.e., the second truck had more effect than the first truck on the oncoming vehicle).

↓ = Significant decrease in MOE for second truck type (i.e., the second truck had less effect than the first truck on the oncoming vehicle).

□ = Insufficient sample size.

Results of the MOE comparisons were produced for eight different combinations of geometric conditions on the basis of lane width (10 or 11 ft and 12 or 13 ft), shoulder width (less than 4 ft, and 4 ft or greater) and curvature (tangent and curve). On the basis of lateral placement changes of ≥1 ft, the semi-45 faired significantly worse than the semi-40 for two geometric groups having narrow lanes and shoulders. The double caused significantly more oncoming vehicles to change their lateral placement than the semi-48 on narrow tangents. The semi-48 with axles back actually fared better than the semi-45 in two instances, which could be the result of the more conservative driving when the drivers operated the semi-48 with axles back (i.e., because the truck was driven slightly farther from the centerline than the semi-45).

Results of the analysis of edgeline encroachments revealed no significant differences between most truck types for a great majority of roadway situations. Significant differences existed in three situations, where (a) semi-45 showed significantly more edgeline encroachments than the semi-40 (for wide lanes and shoulders on curves), (b) the semi-48 had more encroachments than the semi-40 (for narrow lanes and wide shoulders on tangents), and (c) the double had more encroachments than the semi-40 on narrow lanes with wide shoulders on tangents. Results of the *Z*-tests showed a mix of results with no clear trends.

A summary of the comparison of trucks using the analysis of covariance on continuous MOEs is presented in Table 5. Results of testing with the continuous MOEs are given separately for two conditions.

1. Restrictive geometric segments (curves with lane widths of 10 or 11 ft, and shoulders of less than 4 ft); and
2. Nonrestrictive geometrics segments (tangents with lane widths of 12 or 13 ft and shoulders of 4 ft or more).

For the analysis of covariance testing, control variables were used where appropriate to adjust mean values of the MOEs for the influence of such factors as state (New Jersey or California) and type of oncoming vehicle (car or truck).

A review of the results revealed several trends. For the *Z*-tests conducted on data from the least restrictive conditions (i.e., 12- or 13-ft lanes with 4-ft or wider shoulders), only 1 case out of 44 (with adequate data) showed a difference between truck types. However, applying *Z*-tests to data from the most restrictive geometry (i.e., lane widths of 10 or 11 ft and shoulders of less than 4 ft), more truck comparisons (10 out of 60) were found to have significant differences between truck sizes.

Another finding was that more of the operational differences between truck types occur on tangents than on curves. Although somewhat unexpected, this finding tends to support an earlier finding that the lateral placement change did not change with increasing degrees of curvature. In other words, oncoming vehicles on tangent sections may be more likely to vary their lateral placement than on curves when passing a

TABLE 5 SUMMARY OF TRUCK COMPARISON OF VARIOUS MOEs ON RURAL ROADS USING ANALYSIS OF COVARIANCE (0.05 LEVEL)

| | More Restrictive Geometrics | | | | Less Restrictive Geometrics | | | |
|---|---|---|---|---|---|---|---|---|
| Truck Type Comparison | Lateral Placement at truck | Δ Lateral Placement | Vehicle Speed at Truck | Δ Vehicle Speed | Lateral Placement at Truck | Δ Lateral Placement | Vehicle Speed at Truck | Δ Vehicle Speed |
| Semi 40 vs. Semi 45 | ● | ● | ● | ● | ● | ● | ● | ● |
| Semi 40 vs. Semi 48 (back) | ● | ● | ● | ● | ● | ● | ● | ↑ |
| Semi 40 vs. Semi 48 (forward) | ● | ● | ● | ● | ● | ↑ | ● | ● |
| Semi 40 vs. Double | ● | ● | ● | ● | ● | ● | ● | ● |
| Semi 45 vs. Semi 48 (back) | ● | ↓ | ● | ● | ● | ● | ● | ● |
| Semi 45 vs. Semi 48 (forward) | ● | ● | ● | ● | ● | ↑ | ● | ● |
| Semi 45 vs. Double | ● | ● | ● | ↑ | ● | ● | ● | ● |
| Semi 48 (back) vs. (forward) | ● | ● | ● | ● | ↓ | ↑ | ● | ● |
| Semi 48 (back) vs. Double | ● | ↑ | ● | ● | ● | ● | ● | ● |
| Semi 48 (forward) vs. Double | ● | ● | ● | ↑ | ● | ↓ | ● | ● |

● = No significant difference in MOE.

↑ = Significant increase in MOE for second truck type (i.e., the second truck had more effect than the first truck on the oncoming vehicle).

↓ = Significant decrease in MOE for second truck type (i.e., the second truck had less effect than the first truck on the oncoming vehicle).

large oncoming truck. This behavior may be caused by the larger effect of the curve than by the trucks on vehicle lateral placement.

### *Issue 3b: Differences in MOEs Between Semi-40 and Semi-45*

The semi-45 was different than the semi-40 under some geometric conditions using some MOEs, but overall differences between the two truck types are not strongly supported. The semi-45 was associated with a significant increase in the proportion of vehicles with lateral placement changes of 1 ft or more in narrower lanes with narrower shoulders and an increase in the proportion of vehicles encroaching the edgeline on curved sections with wide lanes and shoulders. However, the semi-45 also was associated with a significantly lower proportion of 5-mph speed changes than the semi-40. No differences in speed, speed change, lateral placement, or lateral placement change were found between the two vehicle types.

### *Issue 3c: Differences in MOEs Between Semi-40 and Semi-48*

Some significant differences were found in which the semi-48 affected oncoming traffic more than the semi-40. However, in a few other situations, the semi-40 affected oncoming traffic more than the semi-48. Analysis of covariance results show that the semi-48 with axles forward was associated with significantly greater lateral placement changes by oncoming vehicles for the less-restrictive geometrics condition. Oncoming motorists moved laterally away from the semi-48 with axles forward an average of 0.52 ft compared with 0.07 ft for the semi-40. Significantly more vehicles were observed over the edgeline on 10- and 11-ft lane tangent sections with wide shoulders when passing the semi-48 with axles back than the semi-40.

By contrast, several instances were found that showed that the semi-40 affected oncoming traffic more than the semi-48. Several instances were found of significantly lower proportions of vehicles experiencing speed changes of 5 mph for the semi-48 with axles back compared to the semi-40. Although somewhat contrary to expected results, these findings could be caused partly by different truck operation and lane placement of the truck types.

### *Issue 3d: Differences in MOEs Between Semi-40 and Double-28*

Of the geometric and MOE conditions tested, only two showed any significant differences between the semi-40 and the double-28. First, for tangent sections with narrower lanes and shoulders, a significantly higher proportion of oncoming vehicles moved laterally 1 ft or more when passing the double, compared with the semi-40. Second, a significantly higher proportion of vehicles encroached the edgeline when passing the double-28 compared with the semi-40 for 10- and 11-ft tangent sections with wide shoulders. However, little or no differences were found in oncoming vehicle operations between the double-28 and semi-40 for most of the two-lane roadway conditions tested. Surprisingly, few operational differences resulted, particularly because the double-28 was driven closer to the centerline than the semi-40.

*Issue 3e: Differences in MOEs Between Semi-45 and Semi-48*

Significant differences were found in several cases. Like the comparison of the semi-40 and the semi-48 in Issue 3c, the comparison of the semi-45 and semi-48 resulted in one truck's affecting traffic significantly in some cases and the other truck's affecting traffic significantly in other cases. Four geometric conditions were found in which the semi-48 (axles back in most cases) caused a higher proportion of speed changes of 5 mph or greater compared with the semi-45. However, the semi-48 was associated with a lower proportion of oncoming vehicles with lateral placement changes of 1 ft or greater for two geometric conditions. Also, a reduction in the average change in lateral placement was found under more restrictive geometric conditions for the semi-48 with axles back, compared with the semi-45. One explanation for these unexpected lateral placement results is the differences in the manner the trucks were driven, as discussed in Issue 2.

*Issue 3f: Differences in MOEs Between Semi-45 and Double-28*

Significant differences were found for a few geometric conditions. Analysis of covariance revealed significantly greater vehicle speed changes for the double-28 in more restrictive geometric conditions. This finding was consistent with other results that revealed a significantly higher proportion of oncoming vehicles with speed changes of 5 mph or greater for the double-28, compared with the semi-45 in cases of narrower roads on curves. An explanation may be partly found in the double-28's being driven closer to the centerline than the semi-45.

The proportion of vehicles with a change in lateral placement of 1 ft or greater was significantly less for doubles than for the semi-45 on tangents with narrow lanes and wide shoulders. However, no differences in average lateral placement change between the semi-45 and double-28 were found by using the analysis of covariance.

In summary, evidence exists that oncoming motorists may slow down more for doubles than for the semi-45, possibly because they see a longer truck and expect a problem. However, the fact that oncoming motorists do not change lateral placement when beside the double-28 may show that the drivers perceived no need for evasive action, possibly because the offtracking of the double-28 on the two-lane roadways rarely presented much of a problem for oncoming traffic.

*Issue 3g: Differences in MOEs Between Semi-48 and Double-28*

Although differences in MOEs were found in several cases, the results are mixed. Few lateral placement changes of 1 ft or greater for oncoming traffic were found for the semi-48 in three cases (all narrow shoulder conditions). However, the average lateral placement change was significantly lower for the double-28 in one case and lower for the semi-48 in another. Average vehicle speed changes were greater with the double in one case of more restrictive geometrics, whereas the double-28 was associated with a lower proportion of speed changes of 5 mph or more for tangent roadways with wider lanes and narrower shoulders.

In summary, the inconsistent results in operations between the double and semi-48 preclude identification of one type as clearly a greater operational problem. The manner of operation of these two truck types was also considered to be a possible factor in the mixed results, as discussed earlier.

*Issue 3h: Differences in MOEs Between Semi-48 Axles Forward and Semi-48 Axles Back*

In three of four situations where significant differences were found, the semi-48 with axles forward was shown to have greater operational effects on oncoming traffic than the semi-48 with axles back. This finding can be explained by the manner in which the two control trucks were operated. As discussed, the semi-48 with axles back was generally driven a greater distance from the centerline than the semi-48 with axles forward (2.06 to 1.84 ft average distance, respectively, which is a significant difference at the 0.10 confidence level but not at the 0.05 level).

*Issue 4: Reactions to Different Control Trucks by Oncoming Traffic*

In a few cases, oncoming traffic was affected considerably by the control trucks, particularly by the semi-48 and the double-28. The previous analyses involved average vehicle operations for various sample sets. However, efforts were also made to review extreme reactions to the various control trucks by oncoming traffic, as a possible indication of near-miss accidents.

Four operational MOEs were analyzed including

- Change in lateral placement (ft) of oncoming vehicles (i.e., how far an oncoming vehicle moved over in the lane in response to the oncoming control truck);
- Change in speed (mph) of oncoming vehicles (for those vehicles that slowed down in response to the control truck);
- Clearance (ft) between control truck and oncoming vehicle; and
- Distance of the vehicle to the right of the edgeline.

For each of these measures, the extreme value (maximum or minimum) and the first and third percentile values were determined for each type of control truck and are presented in Table 6 for all sites. The largest changes in lateral placement were a 5.5-ft movement by a motorist in response to the double-28, and a 4.8-ft movement by a motorist for the semi-48 with the axles back. However, first percentile values were nearly identical between truck types, ranging from 2.3 to 2.6 ft (highest for the semi-48 with axles back). At the third percentile, values for different trucks were also close and

TABLE 6 SUMMARY OF THE EXTREME REACTIONS TO CONTROL TRUCKS BY ONCOMING VEHICLES

| Operational Measure | Measure Value | Truck Type: Semi 40 | Semi 45 | Semi 48 (axles back) | Semi 48 (axles forward) | Double |
|---|---|---|---|---|---|---|
| Change in lateral placement of oncoming vehicles (feet) | Maximum<br>1 Percentile<br>3 Percentile | 3.2<br>2.3<br>1.6 | 3.3<br>2.3<br>1.6 | 4.8<br>2.6<br>1.7 | 3.5<br>2.4<br>1.7 | 5.5<br>2.3<br>1.9 |
| Change in speed of oncoming vehicles (mph) | Maximum<br>1 Percentile<br>3 Percentile | 20.0<br>9.0<br>6.0 | 13.0<br>7.0<br>4.0 | 19.0<br>12.0<br>5.0 | 21.0<br>12.8<br>8.0 | 24.0<br>8.0<br>5.5 |
| Clearance between control truck and oncoming vehicles (feet) | Maximum<br>1 Percentile<br>3 Percentile | 2.9<br>3.8<br>4.3 | 2.9<br>3.4<br>4.1 | 2.8<br>3.4<br>3.8 | 2.9<br>3.1<br>3.5 | 2.5<br>3.3<br>3.8 |
| Distance of oncoming vehicles beyond edgeline (feet) | Maximum<br>1 Percentile<br>3 Percentile | 3.9<br>1.2<br>0.3 | 4.6<br>1.2<br>0.4 | 1.7<br>1.3<br>0.5 | 2.1<br>1.0<br>0.0 | 2.6<br>1.2<br>0.6 |

ranged from 1.6 ft (for the semi-40 and semi-45) to 1.9 ft (for the double-28).

Maximum change in speed came in response to the double-28 (24 mph) and the semi-48 with axles back (21 mph). The semi-40 had an unexpectedly high 20-mph speed reduction in one case. At the first percentile, the greatest speed reduction came from the semi-48, with 12.8- and 12.0-mph speed changes in response to the axles forward and axles back condition, respectively.

Minimum clearances between control trucks and oncoming vehicles ranged from 2.5 ft (double-28) to 2.9 ft (three truck types). For the first and third percentile levels, clearances were generally slightly less for the semi-48 and double-28 than for the semi-45 and semi-40.

Maximum edgeline encroachments were found for the semi-45 (4.6 ft) and semi-40 (3.9 ft). However, the first percentile values were consistent with other MOEs with the greatest value (1.3 ft) for the semi-48 with axles back. At the third percentile, the double-28 and semi-48 with axles back caused the highest values of 0.6 and 0.5 ft, respectively.

This analysis showed that there are isolated extreme operational incidents that occur because of oncoming vehicles passing large trucks. Keeping in mind that a single maximum or minimum value may be influenced by many factors other than truck type, the trend to greater extreme values (i.e., at the first and third percentile levels) is indicated for the semi-48 and double-28. However, differences at these levels are generally small and may be within the range of the standard error of the data.

## SUMMARY AND CONCLUSIONS

The ability of various truck configurations to negotiate roads and streets with restrictive geometry was studied in addition to the effects of such trucks on traffic operations and safety of such roads and streets. Truck sizes included truck-tractor semitrailers with trailer lengths of 40, 45, and 48 ft and trailer widths of 96 and 102 in., and twin-trailer combinations with 28-ft trailers.

Also included was a review of literature and an analysis of offtracking of truck sizes of concern. Test sites consisted of rural two-lane roads in New Jersey and California with lane widths of 10 to 13 ft, shoulder widths ranging from 0 to approximately 10 ft, and different types of horizontal alignment (tangents, gentle curves, severe curves).

Control trucks were used for testing at the sites (i.e., staged experiments using a professional driver and rented truck tractors and trailers). Statistical testing using *t*-test, analysis of variance and covariance, *Z*-test for proportions, and other tests were conducted to compare operational differences between the various truck types.

### Findings

Roadway geometrics that affect vehicle operations relative to large trucks on rural, two-lane roads include lane width, shoulder width, and presence of curvature. Wider (12 or 13 ft) lanes allow opposing vehicles to move farther right in encounters with trucks and fewer vehicles cross the edgeline with wider lanes. Wider (4 ft or greater) shoulders generally allowed opposing vehicles to accelerate to regain their free-flow speed, move farther to the right, and cross the edgeline more frequently while passing the truck. Presence of curvature usually meant greater operational changes (i.e., speed changes) and undesirable maneuvers by opposing vehicles. Degree of curvature had little effect on lateral-placement MOEs over the ranges tested, but large degrees of curvature (i.e., 7° to 15°) did cause opposing vehicles to slow while passing large trucks.

Drivers of the control trucks compensated for the greater offtracking of the semi-48 with axles back by driving farther from the centerline than the semi-48 with axles forward or the double-28. In fact, no differences were found in average distance to the centerline or in clearance between the trucks and opposing vehicles between the semi-48 with axles back, semi-40, and semi-45. Driver skill and caution on rural roads seemed important in the operation of vehicles that interact with the large trucks.

Some statistically significant differences in MOEs were found between the larger trucks (semi-48 and double-28) and smaller trucks (semi-40 and semi-45). However, these differences were numerically quite small. Oncoming motorists moved away from the semi-48 with axles forward or the double-28 more than the semi-40 and strayed over the edgeline for the semi-48 with axles back or the double-28 more often than for the semi-40. The semi-48 and double-28 also caused motorists to make 5-mph (or more) changes in speed more often than the semi-45. However, in general, the results showed many situations in which no significant operational differences existed between truck types. Also, significant differences were found in a few cases with the smaller truck in the comparison causing greater operational changes than the larger truck. For the range of conditions tested, other factors such as driver skill (as evidenced by handling of the truck) and roadway geometrics seemed to affect the operations of oncoming vehicles on two-lane, rural roads as much or more than truck type.

Analysis of extreme values for certain MOEs (as a measure of near-miss accidents) showed that a few drastic speed changes and lateral placement changes did occur by oncoming vehicles when passing large trucks. The semi-48 with axles either forward or back and the double-28 were generally associated with more extreme changes by oncoming motorists than the semi-40 and semi-45.

### Implications of Study Results

The results have several implications with respect to operational effects of larger trucks. The literature review and offtracking data indicate that truck width is a less important issue than truck length for the trucks of interest. All field testing was thus conducted with emphasis on truck length and configuration. Placement of the rear axles was also studied in the case of the semi-48.

Truck drivers often handle the larger trucks (i.e., semi-48s and double-28s) differently than the smaller trucks (i.e., semi-40s and semi-45s). Different handling can at least partly compensate for increased offtracking and length of the larger trucks, and may mean fewer operational problems than might otherwise be expected.

Test sites used were selected to be only somewhat restrictive because severe encroachments were not desirable in field testing. However, some of the sites approached the limits of geometric conditions at which more effects of the larger trucks became evident. In particular, the semi-48 with axles back caused more operational problems on rural two-lane roads with narrow lanes and narrow shoulders.

A variety of test conditions and MOEs were used. In spite of this variety, the results do not provide sufficient information for recommending blanket regulations for larger trucks. However, it was evident that combinations of geometric conditions at a site must be considered before establishing truck restrictions. For example, 12-ft lanes combined with sharp horizontal curves on a rural, two-lane road can lead to more operational problems for larger trucks than on 11-ft lanes on a tangent section.

### Recommendations for Future Research

Tests were primarily conducted under ideal conditions. Most of the results were based on two highly experienced drivers, knowledgeable of the experiment purpose, operating trucks in good condition over known routes with dry pavement during the day. Thus, a need remains for knowledge of large truck operation in the general traffic stream under less-than-ideal conditions. Operational problems associated with larger trucks may be caused by inexperienced or impaired drivers with faulty equipment in severe weather, and these and other less-than-ideal conditions should be examined.

Several other issues exist involving larger trucks that could use additional scrutiny. Ranges of geometric conditions not covered in this study remain an issue because they pertain to inclusion in the National Truck Network. For example, same-direction passing of wider and longer trucks on narrow, multilane highways has emerged as a concern. Also, longer semitrailers (i.e., 53-ft) are now allowed by most states with unknown effects on operations and safety.

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