Effects of Turns by Larger Trucks at Urban Intersections

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This paper gives results and conclusions from part of a study done for the Federal Highway Administration on the safety and operational effects of large truck operations. Computer simulation and manual observations at six intersections in California and New Jersey were used to investigate turns by large trucks at urban intersections. The encroachment of a truck into adjacent lanes during a turn was studied using the computer simulation. The field data examined on a particular truck turn included the encroachment, the time to complete the turn, and the conflicts with other vehicles in the traffic stream caused by the truck. Field observations were made of turning trucks in the traffic stream and also of a control truck of known size driven repeatedly through a study intersection by a professional driver who knew the purpose of the experiment. The results showed that small curb radii, narrow lane widths, and narrow total street widths were among the geometric features associated with increased operational problems. The results also showed that large trucks will have little impact (compared with smaller trucks) at most urban intersections of the types tested, but some adverse operational effects should be expected at some intersections. Trailer length was found to be a more critical element to smooth operations than trailer width for the trucks tested. Many site, driver, and equipment factors should be considered before the decision is made to regulate truck traffic in a certain manner.

The Surface Transportation Assistance Act of 1982 (1982 STAA) required some states to change their restrictions on the sizes of trucks operating on their portions of the national truck network of interstate and other designated Federal-aid highways. Due to the 1982 STAA, states may not impose trailer width limits of less than 102 inches. A 96-inch maximum trailer width had been in effect in most states prior to the 1982 STAA. The 1982 STAA also provided that states allow tractor-semitrailer combinations with semitrailer lengths of up to 48 feet and tractor-semitrailer-trailer combinations with semitrailer and trailer lengths of up to 28 feet on the national network. Previously, states had the freedom to impose maximum semitrailer lengths and in some cases had prohibited tractor-semitrailer-trailer combinations.

The interstate and turnpike systems have generally been built to very high geometric standards. However, other Federal-aid systems often contain lower standard design features, which may impact safety and necessitate limiting operations of the large trucks specified in the 1982 STAA. It was, therefore, timely to evaluate the impacts of large truck operation on roads and streets with restrictive geometry and to provide insights relative to the selection of routes for the national network.

This paper gives results and conclusions from part of a study done for the Federal Highway Administration (FHWA) on the safety and operational effects of large truck operations (*1*). Two particular situations were identified for study: truck negotiation of winding rural roads and truck turns at urban intersections. This paper details only the urban intersection portion of the study.

A review of previous research revealed that some operational problems are expected when large trucks make turns at urban intersections, but many questions on the issue remain unanswered. An analysis in Texas of the impact of different truck sizes on a variety of geometric conditions concluded that increases in allowed truck size may warrant highway design standard changes (*2*). A 1982 study conducted in Ontario, Canada, showed that large trucks, including tractor-semitrailer-trailer combinations, offtrack (swing wide during turns) farther than smaller trucks (*3*). A study by the Western Highway Institute showed that longer combinations required extra lanes or overlapped into adjacent lanes to negotiate right-angle turns at intersections (*4*). Tractor-semitrailer-trailer combinations were observed in California to use extra lanes, traverse curbs and channels, and use excessive time during turns at intersection (*5*). A 1981 field study that attempted to correlate increase in truck size with operational problems at several sites, including intersections, concluded that increased truck lengths were associated with only negligible operational traffic effects, however (*6*).

Two investigation methods were employed during the study of larger truck turns at urban intersections. A computer simulation technique was used to analyze the offtracking of different sizes of trucks during different turning maneuvers. The simulation provided information that may be useful in selecting routes for the national network. In addition, turning trucks were observed at actual intersections during the study. The field observations allowed comparisons between different truck sizes for particular intersections, which may be useful in predicting the impact of large truck operations.

COMPUTER SIMULATION OF TRUCK TURNS

The turning characteristics of larger trucks were investigated using the Vehicle Offtracking Model and Computer Simulation developed by FHWA and the University of Michigan Transportation Research Institute. The software package

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allowed plotting of the positions of the outside edges of the tractor and trailer(s) and the positions of the tires as a given type of truck completed a turn at an intersection with a given configuration. From such a plot, a more useful plot of the area covered by the truck during the turn was made and analyzed.

The simulation was run for eight types of larger trucks: a tractor-semitrailer combination with a 48-foot semitrailer that was 96 inches wide (semi 48), a semi 48 that was 102 inches wide (semi 48 wide), a tractor-semitrailer combination with a 55-foot semitrailer that was 96 inches wide (semi 55), a semi 55 which was 102 inches wide (semi 55 wide), a tractor-semi-trailer-trailer combination with 28-foot trailers that were 96 inches wide (double 28) a double 28 that was 102 inches wide (double 28 wide), a tractor-semitrailer-trailer-trailer combination with 28-foot trailers that were 96 inches wide (triple 28), and a triple 28 that was 102 inches wide (triple 28 wide). Each of the eight truck types was run over many combinations of angle and radius of turn which are representative of intersections in the United States.

Two measures were used to analyze the offtracking plots produced from the simulation runs. The maximum offtracking distance was recorded for each plot. This distance represents the widest swing of a truck during a turn, as shown in figure 1. The other measure employed was the lane encroachment of the truck during the turn. The lane encroachment was defined as the distance between the curb and the farthest edge of the truck's path measured at the end of the curvature of the curb (at the stop bar of the street onto which the truck is turning). The lane encroachment was measured from the simulation plot by aligning the point of maximum offtracking and the center of the curve of the curb as shown in figure 2. The significance of the lane encroachment is seen, for example, by a truck turning onto a four-lane street with 12-foot wide lanes. If the lane encroachment of the truck for the angle and radius of turn at the intersection is greater than 24 feet, the truck cannot complete the turn without crossing the centerline of the street onto which it is turning. If there is a vehicle idling next to the centerline at the stop bar of that street, the truck cannot complete the turn.

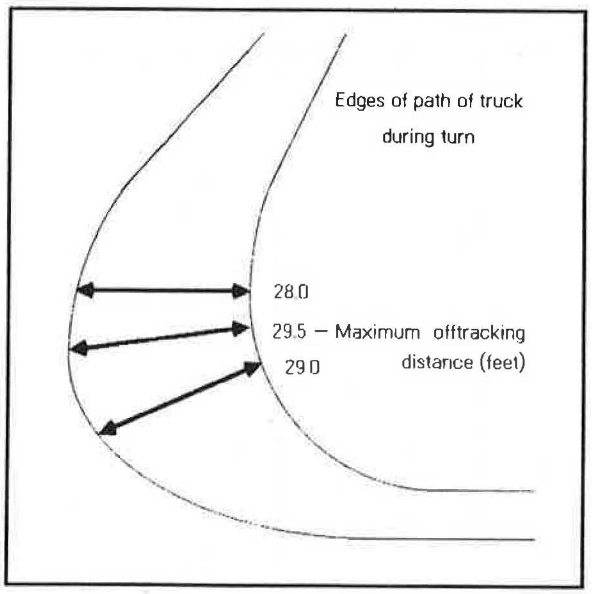


FIGURE 1 Illustration of measurement of maximum offtracking distance.

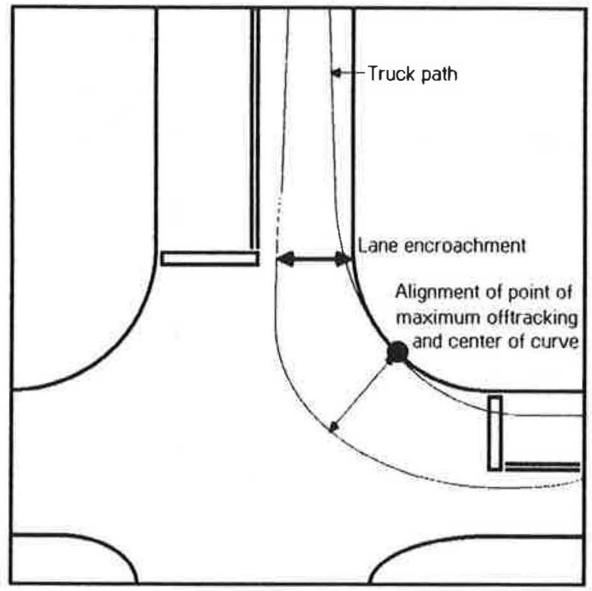


FIGURE 2 Illustration of measurement of lane encroachment.

A summary of the simulation results is given in tables 1 and 2 for the maximum offtracking distance and the lane encroachment measures, respectively. From tables 1 and 2, it can be seen that the most serious operational problems at intersections can be expected (of the eight large truck types examined) from the semi 55 wide. Other truck types, in descending order of space required, are the semi 55, the semi 48 wide, and semi 48, the triple 28 wide, the triple 28, the double 28 wide, and the double 28.

Tables 1 and 2 also show that, for a given trailer configuration and length, 102-inch wide trucks generally exhibited greater maximum offtracking distances and greater lane encroachments than 96-inch wide trucks, but the difference was usually only 0.5 or 1.0 feet. Thus, for the field observations reported later, the issue of the width of the turning trucks was ignored, and the effort was directed at examining the effects of different trailer lengths and configurations.

Table 2 also provides guidance for the selection of truck routes. In general, lane encroachment magnitudes were large (that is, the truck would cross the centerline on a four-lane street) for most larger angles of turn for radii of 22 and 40 feet. Greater intersection angles did not necessarily mean greater lane encroachment values for most truck types, however. Only the semi 55 and semi 55 wide displayed generally greater lane encroachments with greater intersection angles.

The results shown in tables 1 and 2 should be used judiciously, since the simulation was limited in a number of ways. Differences between individual truck drivers may be great enough to overcome the effects of different-size vehicles, but such variability was not included in the simulation. The reactions of the drivers of other vehicles in the traffic stream and the volume of such other vehicles were also omitted from the simulation. Finally, the speed of a turn was not an output of the simulation. This is a serious limitation since a truck driver who slows a great deal in order to complete a turn without encroaching on the centerline or curb may cause as great a

TABLE 1 MAXIMUM OFFTRACKING DISTANCES USING SIMULATION

Truck type	Maximum offtracking distances, in feet, for given angles of intersection in degrees and curb radii in feet														
	angle=60			angle=70			angle=90			angle=105			angle=120		
	R=20	R=40	R=60	R=20	R=40	R=60	R=20	R=40	R=60	R=20	R=40	R=60	R=20	R=40	R=60
Semi 48	23.5	21.0	*	*	*	*	31.0	25.5	22.0	35.0	28.0	*	39.0	29.0	*
Semi 48 Wide	24.0	22.0	*	*	*	*	31.0	26.0	22.5	35.0	28.0	*	39.5	29.5	*
Semi 55	*	23.0	21.0	28.0	25.0	22.5	33.5	28.5	*	38.0	31.0	*	43.0	33.5	*
Semi 55 Wide	*	23.5	22.0	29.0	26.0	23.0	34.0	29.0	25.5	38.5	31.5	*	43.0	34.0	27.5
Double 28	20.0	17.5	16.0	21.5	18.5	16.5	25.0	20.0	*	28.0	21.0	17.0	30.0	22.0	17.5
Double 28 Wide	*	18.0	16.0	22.0	18.5	16.5	25.5	21.0	18.0	28.0	21.5	*	30.5	22.5	18.0
Triple 28	*	20.5	18.0	25.0	22.0	19.0	30.0	25.0	*	33.0	26.0	*	37.0	28.0	*
Triple 28 Wide	*	21.0	19.0	26.0	22.5	20.0	31.0	25.5	21.5	34.0	27.0	*	39.0	28.0	*

* - No data were recorded.

TABLE 2 LANE ENCROACHMENT DISTANCES USING SIMULATION

Truck type	Lane encroachment distances, in feet, for given angles of intersection in degrees and curb radii in feet														
	angle=60			angle=70			angle=90			angle=105			angle=120		
	R=20	R=40	R=60	R=20	R=40	R=60	R=20	R=40	R=60	R=20	R=40	R=60	R=20	R=40	R=60
Semi 48	22.0	21.0	*	*	*	*	27.0	22.0	19.0	27.0	22.5	*	28.0	21.5	*
Semi 48 Wide	23.5	21.5	*	*	*	*	26.0	22.0	20.0	27.5	22.5	*	27.5	22.0	*
Semi 55	*	22.5	19.0	27.0	24.0	20.5	30.0	26.0	*	32.0	27.0	*	33.5	26.0	*
Semi 55 Wide	*	22.5	19.0	27.5	25.0	21.0	29.5	25.0	23.0	31.0	26.0	*	33.0	25.0	21.0
Double 28	18.5	16.5	14.0	20.0	17.0	15.0	20.0	17.0	*	21.5	17.0	*	20.5	15.5	12.5
Double 28 Wide	*	17.0	15.0	20.5	17.0	15.0	21.0	17.0	15.0	22.0	18.0	*	21.5	17.0	14.0
Triple 28	*	18.5	16.5	22.5	20.0	16.5	25.0	20.5	*	26.5	21.5	*	24.5	19.5	*
Triple 28 Wide	*	19.0	17.0	24.0	20.5	16.5	25.0	21.0	18.0	27.0	22.0	*	24.5	20.0	*

* - No data were recorded.

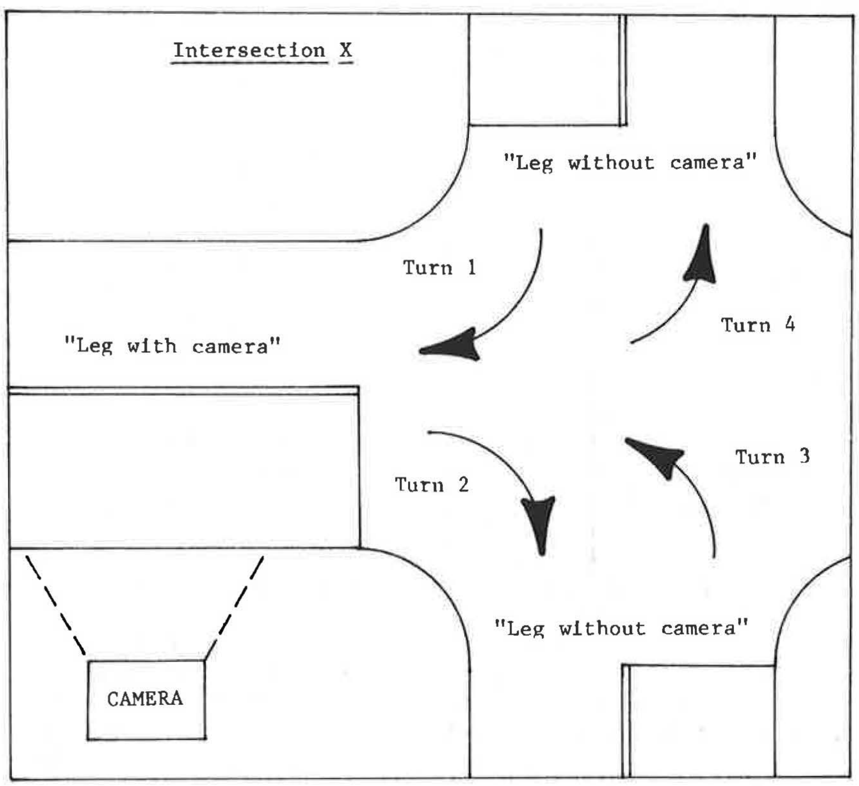
traffic operation or safety problem as a truck driver who does encroach on the centerline or curb.

FIELD OBSERVATION METHODOLOGY

The discussion of the field observation methodology and data in the following sections is given in terms of a specific turn at an intersection, or site. Each site was assigned a two-digit number for identification as shown in figure 3. The first digit of the site number represents the intersection number (for example, 1 through 6, since data were collected at six intersections). The second digit of the site number represents the specific turn at the intersection. A "1" in the second digit represents a right turn onto the leg of the intersection where the data collection camera was stationed, a "2" represents a right turn from the leg with the camera, a "3" represents a left turn onto the leg with the camera, and a "4" represents a left turn from the leg with the camera.

Intersections for the field observation of turning trucks were chosen on the basis of a number of criteria. It was desired that the study should include at least two states in different regions of the United States, and New Jersey and California were chosen. Those states had relatively large samples of large trucks operating on non-freeway routes, and officials in those states were willing to cooperate with the study. Intersections within those states were sought that had large volumes of turning truck traffic as well as certain geometric and traffic features, such as available observer positions, no channels or median barriers, no protected signal phases, no recessed stop bars, 90-degree turns, and minimal pedestrian volumes. It was desired that other geometric features such as lane widths, numbers of lanes, and curb radii vary between the observed intersections. Six intersections that were considered to best fit these criteria were selected. Some of the geometric features that varied among intersections are shown in table 3. The intersections range from a major intersection of seven-lane and five-lane arteries to a three-legged unsignalized intersection between four-lane and two-lane collector streets.

Both left and right turns by trucks were observed in the field. The measures of effectiveness (MOEs) examined during observations of truck turns included encroachments into adja-



"Site X1" refers to intersection X, turn 1.

"Site X2" refers to intersection X, turn 2.

"Site X3" refers to intersection X, turn 3.

"Site X4" refers to intersection X, turn 4.

FIGURE 3 Field observation site numbering system.

TABLE 3 FIELD OBSERVATION SITE CHARACTERISTICS

Characteristic \ Intersection	1	2	3	4	5	6
State	NJ	NJ	Calf.	Calif.	Calif.	Calif.
Number of legs	4	4	4	4	3	3
Number of lanes, leg with camera	3	2	7	5	2	4
Number of lanes, legs without camera	4	4	5	4	4	4
Avg. lane width (ft.), leg with camera	16	11	12	10.5	12	10
Avg. lane width (ft.), legs without camera	12	10.5	12	10	10	11
Width of lane from which turn 1 was made (ft.)	No Turn	11	13	11	10	12
Width of lane from which turn 2 was made (ft.)	17	11	14	13	12	10
Avg. curb radius (ft.), turn 1	No Turn	45	55	32	12	40
Avg. curb radius (ft.), turn 2	21	55	55	35	12	32
Signalized?	Yes	Yes	Yes	Yes	No	Yes
Protected turn phases?	For turn 3 only	No	No	No	Not applicable	No

cent lanes, over the centerline, and over the curb; traffic conflict events such as weaving, stopping, and backing by vehicles into the traffic stream and by the truck; and the clearance time of the truck through the intersection. The clearance time was defined for trucks making right turns and trucks making rolling left turns (in other words, no impeding traffic forced the truck to stop beyond the stop line) as the difference between the time the front tires of the truck crossed the stop bar of the origin street into the intersection and the time the rear tires of the truck crossed the stop bar of the destination street. For left-turning trucks delayed by impeding traffic when they were beyond the stop bar of the origin street, the clearance time was defined as the difference between the time the truck began rolling forward and the time the rear tires crossed the stop bar on the destination street. Since there were very few rolling left turns completed by the trucks at most sites, the analyses were not biased by the use of the two definitions.

The hypotheses tested using the field observations were that larger trucks did not degrade operations at particular turns as measured by the MOEs in comparison to pre-STAA trucks. Larger trucks of interest were the semi 48 and the double 28. The semi 55, triple 28 and other larger trucks were not in common use at the times and locations of testing so adequate samples were not available for observation. Pre-STAA trucks of interest were the tractor-semitrailer combinations with semitrailer lengths of 40 feet (semi 40) and 45 feet (semi 45).

Manual observation was used to collect MOE data on turning trucks. A team of three observers stationed on different corners of the intersection examined turning trucks selected for study, with each observer recording only those MOEs for which he/she had the best view (each observer looked for different MOEs, depending on the turn the truck was making). A fourth observer recorded clearance time, using a stopwatch. A fifth observer photographed each truck selected for study. The slides of the photographs, taken from a known

distance at ground level, were later projected onto a screen, scaled off, and used to obtain the truck dimensions. Other clues, such as the number of 4-foot wide panels on the side of the trailer and the trailer size printed on the side of the trailer, were used to corroborate the scaled estimates of the truck dimensions.

Up to four different turns were observed at each intersection—each turn originating from or destined for the leg of the intersection on which the camera was stationed. Trucks approaching the intersection apparently ready to make one of the four turns were assigned an identification number and communication between the observers via walkie-talkie ensured that all observers were viewing the same truck. Observations were made only during daylight hours with dry pavement conditions.

The manual data collection method proved sensitive and accurate. Pretests with several people recording conflict and encroachment data at one observer position simultaneously and independently showed a high degree of correlation among observers. The photographic method of estimating truck size, when checked with trucks of known dimensions, proved sufficiently accurate to obtain trailer lengths within one foot of the actual length.

During the test period at the two New Jersey intersections (intersection numbers 1 and 2), control trucks were used to ensure adequate samples of certain types of trucks. These control trucks (a semi 40, a semi 48, and a double 28) were driven through the intersections repeatedly by a professional driver who knew the purpose of the testing.

FIELD OBSERVATION DATA

Data were collected on a total of 1,151 turning trucks, as shown in table 4. The sample included 412 semi 40s (108 control trucks and 304 trucks in the traffic stream), 443 semi 45s (all traffic stream), 177 semi 48s (90 control and 87 traffic stream), and 119 double 28s (61 control and 58 traffic stream). The samples per intersection ranged from 132 trucks at intersection 3 to 308 at intersection 1. Small samples of semi 48s and double 28s were collected at some intersections. It is not assumed that the sample of turning trucks observed is representative of the states of California and New Jersey or of the United States. Summary data from the field tests are given in tables 5, 6, and 7 for turn time, the proportion of trucks committing at least one encroachment, and the proportion of trucks causing at least one vehicle conflict, respectively.

COMPARISONS AMONG SITES

During the analysis of the field observation data, comparisons were made among sites to see where the most operational problems from large trucks can be expected and to see whether the sites were similar enough to warrant pooling the data. Pooling the data for different sites would allow larger sample sizes of semi 48 and double 28 observations to be formed which would allow more powerful testing among truck types.

Turn times for the traffic stream semi 45 (for which observations were plentiful at most sites) were compared for each pair of right turns at signalized intersections using the *t*-test. The tests revealed that the right turns from the leg with the camera at intersections 1 and 3 (sites 12 and 32) had significantly faster turn times (at the 0.05 level) than several other sites. These differences were not surprising, since table 3 shows that those sites had a relatively wide turn lane and a relatively long curb radius, respectively. Thus, the data from the remaining signalized right turn sites were pooled for comparisons of turn times between different truck types. In a similar series of *t*-tests using semi 45 turn times on signalized left turn sites, the left turn to the leg with the camera at intersection 1 and both left turns at intersection 4 (sites 13, 43, and 44, respectively)

TABLE 4 SAMPLE SIZES OF TRUCK TYPES AT INTERSECTIONS

Truck type	Number of trucks observed at intersection						
	1	2	3	4	5	6	All intersections
Control - Semi 40	48	60	0	0	0	0	108
Control - Semi 48	60	30	0	0	0	0	90
Control - Double 28	29	32	0	0	0	0	61
Traffic - Semi 40	63	30	44	42	67	58	304
Traffic - Semi 45	94	67	42	65	121	54	443
Traffic - Semi 48	14	9	17	21	6	20	87
Traffic - Double 28	0	0	29	17	2	10	58
All truck types	308	228	132	145	196	142	1151

TABLE 5 FIELD OBSERVATIONS OF TURN TIME

Truck type	Inter-section number	Mean turn time (seconds) with sample size in parentheses			
		Right Turn		Left Turn	
		Turn 1	Turn 2	Turn 3	Turn 4
Control - Semi 40	1	(0)	7.56 (24)	7.21 (24)	(0)
	2	(0)	6.52 (30)	7.80 (30)	(0)
Control - Semi 48	1	(0)	7.98 (31)	9.15 (27)	(0)
	2	(0)	8.41 (15)	8.23 (14)	(0)
Control - Double 28	1	(0)	8.58 (16)	7.95 (16)	(0)
	2	(0)	8.22 (16)	9.16 (16)	(0)
Traffic - Semi 40	1	(0)	7.93 (26)	7.48 (16)	8.16 (21)
	2	7.76 (15)	8.35 (5)	6.85 (6)	10.95 (4)
	3	8.42 (4)	6.27 (14)	8.51 (13)	7.70 (13)
	4	12.63 (16)	11.88 (6)	11.70 (10)	10.32 (10)
	5	8.87 (5)	8.82 (23)	9.36 (36)	9.54 (2)
	6	8.22 (24)	7.79 (1)	8.85 (11)	9.80 (22)
Traffic - Semi 45	1	(0)	8.75 (42)	7.91 (34)	8.76 (18)
	2	10.17 (19)	8.66 (13)	9.06 (23)	10.31 (12)
	3	7.79 (9)	7.38 (15)	9.73 (12)	7.62 (6)
	4	10.40 (22)	11.96 (10)	10.51 (18)	10.76 (15)
	5	10.40 (6)	10.30 (49)	8.76 (63)	9.60 (3)
	6	8.62 (20)	6.73 (1)	9.39 (5)	9.13 (28)
Traffic - Semi 48	1	(0)	8.14 (8)	7.65 (5)	11.18 (1)
	2	6.77 (4)	7.87 (2)	8.93 (1)	13.19 (2)
	3	9.36 (3)	7.14 (4)	7.44 (4)	7.07 (6)
	4	12.42 (8)	15.71 (1)	9.03 (6)	11.72 (6)
	5	(0)	9.67 (4)	7.68 (2)	(0)
	6	7.31 (4)	5.95 (1)	9.86 (1)	9.46 (14)
Traffic - Double 28	3	6.66 (4)	6.34 (1)	9.66 (12)	11.62 (12)
	4	9.22 (8)	8.45 (1)	(0)	12.09 (8)
	5	(0)	(0)	9.24 (2)	(0)
	6	6.67 (3)	17.69 (1)	(0)	9.18 (6)

exhibited significantly different turn times (at the 0.05 level) than other sites. Site 13 had lower turn times, probably due to the protected turn signal phase for that turn. Sites 43 and 44 had higher turn times, due perhaps to the combination of narrow turn lanes and narrow destination streets. Data from the remaining signalized left turn sites were pooled in comparisons between truck types using turn times.

The proportion of semi 40s, semi 45s, and double 28s that committed at least one encroachment was compared for each pair of sites using the Kruskal-Wallis One-Way Analysis of Variance test. Significant differences were found to exist (at the 0.05 level) between each site and at least three other sites. Individual site characteristics apparently play a large role in the incidence of encroachments by turning trucks. A similar statistical analysis using vehicle conflict MOEs was not possible due to small numbers of conflicts at most sites, but inspection of the data does suggest variations in rates of conflict between sites. Thus, the conflict and encroachment data from different sites were not pooled.

A combination of several site characteristics appear to affect the encroachment rates, including lane widths, curb radii, stop bar location, and the number of lanes. Encroachment rates were relatively high at the right turn onto the leg with the camera at intersections 4 and 6 (sites 41 and 61, respectively) which has narrower turn lanes and narrower widths on the destination street than some other sites. Conversely, there was a relatively low proportion of encroachments at the right turn onto the leg with the camera at intersection 3 (site 31) where there was a wide turn lane and a long curb radius. Encroachment rates were relatively high at the left turn onto the leg with the camera at intersections 1 and 5 (sites 13 and 53, respectively), with only one lane on the target streets and stop bars set close to the intersection, and at the left turn from the leg with the camera at intersection 4 (site 44) with

TABLE 6 ENCROACHMENT DATA FROM FIELD OBSERVATIONS

Site number	Number of trucks with one or more encroachments/Observed total of trucks						
	Truck type						
	Control Semi 40	Control Semi 48	Control Dbl. 28	Traffic Semi 40	Traffic Semi 45	Traffic Semi 48	Traffic Dbl. 28
12	7/24	31/31	5/14	19/26	29/42	7/8	
13	3/24	25/29	5/15	14/16	28/34	5/5	
14				7/21	7/17	0/1	
21				13/15	19/19	4/4	
22	0/30	15/15	15/16	5/5	13/13	2/2	
23	0/30	11/15	2/16	1/6	8/23	0/1	
24				2/4	11/12	2/2	
31				0/4	4/9	1/3	2/4
32				6/14	8/15	4/4	0/1
33				0/13	0/12	0/4	0/12
34				1/13	4/6	0/6	3/12
41				15/15	22/22	8/8	8/8
42				6/6	10/10	1/1	1/1
43				5/10	9/18	4/6	
44				7/10	13/15	6/6	4/8
51				6/6	6/6		
52				22/23	48/49	3/4	
53				16/36	41/63	2/2	1/2
54				2/2	3/3		
61				23/24	19/20	4/4	3/3
62				1/1	1/1	1/1	1/1
63				0/11	0/5	0/1	
64				8/22	13/28	6/14	1/6
Total encroachments	10	85	27	179	316	60	24
Total number of trucks	108	90	62	303	442	87	58

a very narrow turn lane. Both left turns at intersection 3 sites (33 and 34), however, with relatively wide left turn lanes and wide destination streets, had virtually no encroachments.

COMPARISONS AMONG TRUCK TYPES

Comparisons were made among the data for control and for traffic-stream trucks of a given size at a given site, with a view toward pooling those observations. In general, t-tests on turn times for sites with sufficient sample sizes showed few differences between control and traffic-stream trucks. However, Z-tests on proportions of conflicts and encroachments for sites with sufficient samples showed many differences between control and traffic-stream trucks. This is reasonable, since the drivers of the control trucks were aware of the experiment and repeated the same turns many times. These drivers were familiar with each site and were likely to exercise special care in making turns, particularly trying to avoid encroaching curbs or centerlines. Thus, in the comparisons among different truck types, the control and traffic-stream observations for a particular truck size at a particular site were not pooled.

The turn-time data were analyzed statistically using the t-test to compare two truck types for a particular site or pool of sites whenever there were at least five observations for each truck type. The t-test results, summarized in table 8, show that there were insufficient samples of turning trucks at many sites to conduct t-tests. For sites with sufficient samples, the test most often supported the hypothesis that there was no difference between truck types. The hypothesis was rejected for two important cases, however. First, in comparisons between semi 40 and semi 48 control trucks at two different sites, one right turn and one left turn, the semi 40 completed turns significantly faster. In both of those comparisons, the mean time for the semi 40 turn was about seven seconds while the mean time for the semi 48 was about nine seconds. It is not

TABLE 7 VEHICLE CONFLICT DATA FROM FIELD OBSERVATIONS

Site number	Number of trucks which caused one or more vehicle conflicts/ Observed total of trucks						
	Truck type						
	Control Semi 40	Control Semi 48	Control Dbl. 28	Traffic Semi 40	Traffic Semi 45	Traffic Semi 48	Traffic Dbl. 28
12	0/24	9/31	0/14	2/26	1/42	1/8	
13	7/24	9/29	3/15	2/16	11/34	1/5	
14				3/21	0/18	0/1	
21				2/15	7/19	2/4	
22	0/30	0/15	0/16	0/5	0/13	0/2	
23	4/30	5/15	6/16	1/6	6/23	1/1	
24				0/4	0/12	0/2	
31				1/4	1/9	1/3	0/4
32				2/14	0/15	0/4	0/1
33				1/13	0/12	1/4	0/12
34				1/13	0/6	1/6	0/12
41				3/16	4/22	4/8	0/8
42				1/6	2/10	0/1	1/1
43				0/10	1/18	1/6	
44				2/10	7/15	2/6	3/8
51				0/6	3/6		
52				1/23	5/49	1/4	
53				8/36	10/63	0/2	1/2
54				0/2	1/3		
61				1/24	3/20	0/4	0/3
62				0/1	0/1	0/1	1/1
63				0/11	0/5	0/1	
64				1/22	3/28	0/14	0/6
Total conflicts	11	23	9	32	65	16	6
Total number of trucks	108	90	62	304	443	87	58

clear why two sites showed differences while at two other sites the comparison of control truck turn times for the semi 40 and semi 48 had no differences. Second, the double 28 proved significantly slower in one comparison of right turn time (a control truck comparison with the semi 40 at site 22) and in four comparisons of left turn time (a control truck comparison with the semi 40 at site 23 and traffic stream comparisons for the pooled data with the semi 40, semi 45, and semi 48). The differences in mean turn times for these comparisons were usually 1.5 to 2.5 seconds. It appears that the double 28 generally had longer turn times where the intersection characteristics were less restrictive, since site 22 had a long curb radius, site 23 had a recessed stop bar, and the pooled data were heavily influenced by data from intersection 3 with less restrictive geometry.

The data in table 6 show that there were differences in the proportions of trucks committing at least one encroachment between truck types at some sites. The differences for the control trucks are large. The semi 48 committed encroachments significantly more often (at the 0.05 level) than the semi 40 at all four sites observed and significantly more often (at the 0.05 level) than the double 28 at sites 12, 13, and 23. The control double 28 committed encroachments at a significantly greater rate (at the 0.05 level) than the semi 40 at site 22 and marginally more often (not statistically significant at the 0.05 level) at sites 13 and 23. The differences between truck types were less apparent for the traffic-stream trucks than for the control trucks, due to smaller samples of the semi 48 and double 28 or to the effects of differences among individual truck drivers who were unaware of the purposes of the observers. Statistical tests were inappropriate for most possible comparisons due to the small samples of semi 48s and double 28s.

Table 7 shows that the proportions of trucks causing a conflict did not vary much at particular intersections between truck types. For control trucks, the semi 48 caused conflicts

TABLE 8 SUMMARY OF *t*-TESTS ON TURN TIME DATA

Truck type comparison		Right turn sites							Left turn sites					
		12	22	32	41	52	61	Site* Group A	13	14	23	53	64	Site* Group B
Control trucks	Semi 40 vs. Semi 48	●	▲	▨	▨	▨	▨	▨	▲	▨	●	▨	▨	▨
	Semi 40 vs. Double 28	●	▲	▨	▨	▨	▨	▨	●	▨	▲	▨	▨	▨
	Semi 48 vs. Double 28	●	●	▨	▨	▨	▨	▨	●	▨	●	▨	▨	▨
Traffic trucks	Semi 40 vs. Semi 45	●		●	●	●	●	●	●	●		●	●	●
	Semi 40 vs. Semi 48	●			●			●	●				●	●
	Semi 40 vs. Double 28				●			●					●	▲
	Semi 45 vs. Semi 48	●			●			●	●				●	●
	Semi 45 vs. Double 28				●			●					●	▲
	Semi 48 vs. Double 28				●			●					●	▲

Note: Sites not shown had insufficient samples for t-test or no data collected for all comparisons.

* - Site Group A includes sites 21, 22, 31, 41, and 42; B includes sites 14, 23, 33, 34, 63, and 64.

□ - Insufficient sample size for t-test.

▨ - No data collected.

● - No significant (0.05 level) difference in average turn time.

▲ - Significant (0.05 level) increase in mean turn time for second truck type.

marginally more often than the semi 40 and the double 28 at site 12, and the semi 48 and double 28 caused conflicts marginally more often than the semi 40 at site 23. Among traffic-stream trucks, a marginal difference among truck types was apparent only at site 41 between the semi 48 and the other truck types. Statistical tests again were generally inappropriate due to the small samples.

Until this point in the report, the fact that many semi 48s have moveable rear axles has not been mentioned. The computer simulation was performed with the rear axles of the semi 48 and semi 55 placed as far to the rear of the semitrailer as possible, and the control truck was also set up in this way. However, for the sample of semi 48s observed in the field, there was a noticeable variety in the position of the rear axles. The photographs of the turning semi 48s were thus examined for rear axle position. Of the 87 traffic-stream semi 48s, 43 had axles placed forward (six to nine feet from the center of the rear set of wheels to the rear of the semitrailer), 36 had axles placed back (three to six feet from the center of the rear set of wheels to the rear of the semitrailer), and eight had axle placements that could not be measured from the photographs. Since the rear axle placement affects offtracking and could affect truck performance on turns in terms of the MOEs studied in the field, the data for semi 48s were examined for the effects of different axle placements. The turn times for the pooled right turns and the pooled left turns were used to compare the semi 48 with axles forward to axles back. For the right turns, the trucks with axles back had a mean time of 11.3 seconds, compared to a mean of 7.3 seconds for the trucks with axles forward. This difference was statistically significant at the 0.05 level using the *t*-test with 16 degrees of freedom. For left turns, the difference in mean turn times was negligible and statistically insignificant. Insufficient samples were available to analyze encroachments or conflicts for the axle positions.

The final step of the data analysis involved a look at the effect of the presence of a vehicle near the turning truck. There was concern that a given truck turned differently depending on whether there was a vehicle beside the truck before the turn or waiting at the stop bar in the center lane of the destination street (in other words, the truck was not free to swing wide during the turn) and that this bias was reflected in the turn time and encroachment results given previously. In addition, there was concern that analysis of the conflict data was biased against high-volume intersections, since low-volume intersections would have a greater proportion of turning trucks with no chance of conflicts (no other vehicles present to conflict with the truck). However, a duplication of the analyses described above using only the data recorded when there were other vehicles present (approximately four-fifths of all observations) showed that no important changes in the results already reported were necessary.

CONCLUSIONS

In reviewing the study results, the limitations of the study methods must be kept in mind. The simulation was limited because the differences among individual truck drivers, the reactions of the drivers of other vehicles in the traffic stream,

and the speed of the turn were not modeled. The field observations were limited because they were based partially on a control truck with a professional driver knowledgeable of the purpose of the observations and because of the small samples of traffic-stream truck data gathered at some sites. The results and conclusions should not be generalized to cover truck types or types of intersections that were not specifically tested.

No blanket regulations on truck routes should be based on this study. Many site, driver, and equipment variables must be examined before the decision to regulate truck traffic in a certain manner can be made. The computer simulation and field observation results showed that different types of trucks perform differently at different intersections and that small curb radii, narrow lane widths, and narrow destination roadways were among the geometric factors associated with increased operational problems.

Semi 48s and double 28s will have little impact on traffic operations at most intersections like those tested, but limited operational problems should be expected at some intersections. The simulation demonstrated that trailer width is not as critical to smooth operations as trailer length, over the ranges of trucks and intersections simulated. Among the larger trucks simulated, the semi 55 would be expected to cause the most operational problems at a given intersection, followed by the semi 48, the triple 28, and the double 28. In field tests, the semi 48 sometimes turned slower, committed more encroachments, and caused more conflicts than the semi 40. The double 28 sometimes turned slower, committed more encroachments, and caused more conflicts than the semi 40, but committed fewer encroachments and caused fewer conflicts than the semi 48. The axle position of the semi 48 made a difference in right turn time, with the larger offtracking of the truck when the axles are back causing a longer turning time, but did not make a difference in left turn time.

Tests in this research were conducted under ideal conditions. Many of the important field test results were based on an experienced driver operating a truck in good condition through a familiar intersection with dry pavement during the day. There remains a need for study of large truck operations under less-than-ideal conditions. Future examinations of large truck operation should include problems associated with inexperienced or impaired drivers, faulty equipment, and wet pavement, for instance.

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