Field Observations of Truck Operational Characteristics Related to Intersection Sight Distance

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Several pilot field studies were conducted to test a data collection methodology for the evaluation of AASHTO Case III–B and C sight distances for trucks at stop-controlled T intersections. The data collection plan used a combination of three traffic observation techniques: video recorders, human observers, and portable traffic data collectors. Specific findings included estimates for the gaps (time and distance) that trucks on a minor road accept during a turn maneuver onto a two-lane roadway, the average acceleration rate for the turn maneuver of a truck on a minor road, and the average deceleration rate of vehicles on a major road during a truck's turn maneuver from a minor road. The speed reduction by a vehicle on a major road during the truck's turn maneuver and the minimum separation distance between the turning vehicle and an oncoming vehicle were also estimated.

Recent sensitivity analyses have demonstrated that the application of AASHTO's intersection sight distance (ISD) procedures to trucks can result in required sight distances that could exceed 3,000 ft (*1*). Such long sight distances are probably not practical or required by truck drivers. To quantify actual truck performance, pilot field studies were conducted to observe truck operational characteristics at three stop-controlled T intersections. Video data were collected at three intersections where trucks exited from a minor two-lane roadway and turned left or right onto a major two-lane roadway. The data collection methodology successfully established estimates of truck gap acceptance values, truck acceleration rates, vehicle deceleration rates and speed reductions on the major roadway, and a resulting minimum separation between the accelerating truck and an oncoming vehicle on the major roadway. Specific findings were compared to vehicle performance characteristics described in AASHTO's 1984 *A Policy on Geometric Design of Highways and Streets* (Green Book) (*2*) and other related literature.

The field data provided guidance for future efforts. Another study on a larger scale is needed to fully evaluate field performance characteristics such as acceleration, deceleration, and minimum separation. The gap acceptance concept should also be further examined for a broader range of vehicle and driver types, intersection geometrics, approach speeds, and traffic volume on the major and minor roads. A gap acceptance sight distance procedure provides a means to simultaneously consider driver behavior, vehicle performance, and operational characteristics at an unsignalized intersection. Knowledge gained regarding the various distributions of the interrelated parameters would establish an empirical basis from which current ISD criteria could be modified. The resulting ISD procedure would specifically permit an analysis of differently designed vehicles commensurate with the intended functional requirements of the intersection.

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DATA COLLECTION

Intersection Selection

Potential intersections were identified through phone calls or discussions with individuals associated with trucking associations, planning commissions, municipalities, police, and state departments of transportation. Candidate intersections satisfied the following conditions or criteria:

- Unobstructed sight distance is present (goal of 1,000 ft).
- Between 5- and 10-percent truck traffic exists on the major road.
- The minor road is associated with a truck generator or with a high percentage of truck traffic.
- Both the major and minor roads are two-lane roadways meeting as a T intersection (preferably without turn lanes).
- The minor road is controlled by a Stop sign.
- The posted speed limit for the major road is greater than or equal to 40 mph.
- The candidate intersection is a minimum of 1,000 ft from a signalized intersection.
- The candidate intersection is standard with regard to geometry (i.e., its approach roads intersect at an approximately 90-degree angle with relatively flat approach grades).

Candidate intersections identified during the initial contacts were visited. Photographs were taken, sketches were drawn, and geometric and operational information was obtained during the initial visits.

Intersections with acceleration lanes, separate left-turn lanes, apparently low truck traffic on the minor road, or apparently low volume on the major road (large headways) were eliminated. Traffic counts were conducted for a minimum of 24 hr at each candidate location. On the basis of information from the initial site visits and the traffic counts, three intersections in Pennsylvania were selected. One intersection was an asphalt and aggregate plant driveway (Central Valley Asphalt Plant), the second was a truck stop exit (Truck Stop 64), and

the third was near an industrial park (Trindle and Railroad). Table 1 presents the characteristics of each intersection.

Data Collection Plan

The primary objective of this pilot study was to develop, test, and recommend an effective data collection approach. A video camera data collection procedure was used at each site. The video equipment recorded the movement of the vehicles at each intersection. This procedure permitted the collection of all data needed for evaluation. Traffic data collectors recorded an estimate of the running speed on the major road and a point speed for the decelerating or accelerating vehicle, as well as the traffic volume during the study. Figure 1 shows the equipment layout for a typical data collection effort.

Data collection began by properly orienting the video cameras. The cameras were positioned to maximize the length of road filmed without jeopardizing the resolution of the vehicles on the film. Typically, one camera recorded the overall operations at the intersection (100 ft on either side of the center of the minor road approach); several other cameras recorded the major roadway approaches. Approximately 300 ft of road was discernible from each approach leg camera.

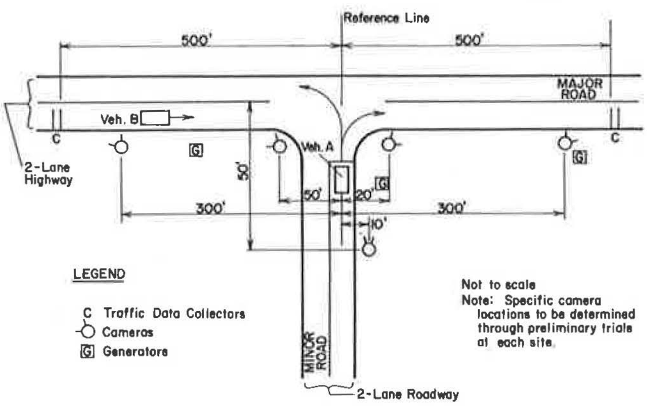

FIGURE 1 Typical setup for video data collection plan.

An internal clock was started when videotaping began. The cameras superimposed the time on the video recording so that the times of specific events could be identified during the data reduction process. Each internal clock was synchronized with a master clock. Researchers used a lap-top portable computer with continuous time display to coordinate the counters and video cameras.

To determine the position of a vehicle at a given time, reference points were documented on the videotape. This was accomplished by flagging vehicles as they passed selected points in the study area. The flagging procedure began at the center of the minor road approach (the reference line shown in Figure 1). Points were then painted in 100-ft increments along the major road up to a distance of 600 ft from the reference line in each direction. The flagging process established the reference scale for eventual data reduction.

Two traffic data collectors (Diamond Traffic Products, Model TT-2001) recorded major roadway approach or departure speeds for individual vehicles. The collectors were generally 500 ft from the intersection on the near-lane legs with tubes spaced 10 ft apart to measure speed, axle classification, and volume. Because the collectors could display and store individual vehicle speeds, manual recording of the speed of each approaching or departing vehicle was not required.

DATA REDUCTION

The data reduction was accomplished by drawing 100-ft increment lines on a clear sheet of acetate taped to a television monitor. The process began by reviewing the videotape frame by frame to determine the exact location of a vehicle crossing a 100-ft increment line.

The videotape of the minor road approach was commonly referred to as the "reference line tape" and was used in every data reduction. Data reduction, although relatively simple, was time consuming and tedious. To reduce the required information (gap, acceleration, deceleration, and minimum separation), several different videotapes were viewed simultaneously. The video equipment had the following capabilities: slow motion, freeze frame, and frame-by-frame advancement.

TABLE 1 SELECTED INTERSECTION CHARACTERISTICS

Intersection No.	Major Road	Minor Road	Volume[a] Major	Volume[a] Minor	% Trucks[a] Major	% Trucks[a] Minor	Speed Limit[b] (mi/h)	85th Percentile Speed (mi/h)	Descriptive Profile Major	Descriptive Profile Minor
1	RT 26	Central Valley Asphalt Plant	14,000	175	15	90	45	47	level	level
2	RT 64	Truck Stop 64	7,000	500	20	95	40	51	level	level
3	Trindle	Railroad	20,000	2,000	20	25	40	40	level	level

[a]Values are unadjusted ADT count volumes obtained in September 1988 during site selection.

[b]Major roadway approach.

Gap Acceptance

The reference line tape was used to reduce the gap information. Data were eliminated if the vehicle on the minor road did not stop, a turning vehicle caused the gap, or the gap-causing vehicle turned onto the major road from a nearby driveway. To obtain the gap data, a record was made of the time the truck on the minor road stopped, the times the subsequent vehicles on the major road crossed the reference line until the departure of the truck, the departure time of the truck, and the time the next vehicle on the major road crossed the reference line.

Acceleration

The equipment setup required for acceleration was more complex than the gap setup. For most sites, three tapes were reviewed simultaneously to obtain complete acceleration information for a particular truck. Acetate sheets were marked in 100-ft increments using the flagging procedure. The monitors were used to follow the truck from screen to screen as the turn maneuver was accomplished. The departure time and the times at which a truck passed the 100-ft increment lines were read from the video screen and recorded in a computer worksheet.

Data for vehicles were eliminated for the following reasons: the vehicle did not stop completely at the intersection, certain 100-ft data points were not discernible, the vehicle slowed to make a turn within the study area, or other factors were present that would bias the findings.

Deceleration

Vehicles on the minor road identified from the gap data that did not stop at the intersection were eliminated from the potential deceleration data set. Deceleration data for vehicles on the major road reacting to a turning truck that accepted a gap greater than 20 sec were also eliminated. (Initial field observations indicated that the vehicle on the major roadway did not decelerate during these truck turning maneuvers.) The potential deceleration data were then divided into the following groups:

- Vehicles in the near lane of the major road responding to right-turning trucks,
- Vehicles in the near lane of the major road responding to left-turning trucks, and
- Vehicles in the far lane of the major road responding to left-turning trucks.

Minimum Separation

Minimum separation is the distance between the rear bumper of the turning truck and the front bumper of a vehicle approaching on the major roadway. Minimum separation can be determined by comparing the acceleration data for the truck on the minor road with the deceleration data for the vehicle approaching on the major roadway. The minimum time (or distance) difference between estimated acceleration and deceleration curves was eventually determined from a plot of the data. A sample of data sets that included both acceleration and deceleration data was selected for the minimum separation evaluation.

ANALYSIS

Gap Acceptance

The quantity of the proposed data to be collected for the gap acceptance analysis was a compromise between a reasonable, realistic data collection effort for a pilot study and the need for adequate data for numerical analysis. Several combinations of vehicle and maneuver types at the intersections had fewer than 50 data points, which was the goal established at the beginning of the data collection efforts. Analysis was conducted only for combinations of at least 15 truck turning maneuvers from the minor road.

The acceptance and rejection data for two possible maneuvers (left or right turns) and two vehicle types (five-axle trucks and trucks with fewer than five axles) were determined for each day. Field observations indicated that the maneuvers made during the filming were typical; for example, no accidents or other unusual situations occurred during the filming period. The individual numerical data files for each day were later merged into three intersection site files.

Several difficulties and biases arose in the measurement of the critical gap. For example, the actual critical gap of an observed single driver cannot be measured. Such difficulties have resulted in the development of different methods for identifying a critical gap. Three methods were initially selected for this study: the Greenshield and Raff methods and the logit model (*3–5*). The logit model was used for the comparison analysis, because it produced descriptive results. Certain results from the Greenshield analyses must be interpreted with caution because of small sample sizes. One small accepted gap length can determine the average minimum acceptable time gap if none or only one of the drivers rejected the same gap size. The Raff method produced results similar to the Logit model.

Choice modeling (such as whether to accept a gap) may be done by using a logistic model to estimate the probability of taking a certain action. Logistic or logit models have been used in previous studies to model the probability of accepting gaps of varying lengths (*6,7*). The simple, dichotomous choice logistic function is

$$P = \frac{1}{1 + e^{-(\beta_0 + \beta_1 X)}} \quad (1)$$

where

P = probability of accepting a gap,
β_0, β_1 = regression coefficients, and
X = variable related to the gap acceptance decision (gap length).

The mean response is a probability when the dependent variable is a 0 or 1 (accept or reject) indicator variable. The

logistic function can be easily linearized with the following transformation:

$$P' = \log_e\left(\frac{P}{1 - P}\right) = \beta_0 + \beta_1 X \qquad (2)$$

where P' equals the transformed probability.

A sample logistic curve and equation for five-axle trucks turning right at the Trindle and Railroad intersection are shown in Figure 2. The probability of accepting a gap is found by solving Equation 2 for a particular time value. The time gap for a 50-percent probability can be found by substituting 0.5 for P as follows:

$$\log_e\left(\frac{0.5}{1 - 0.5}\right) = -9.58 + 1.12 \times X_{50\%} \qquad (3)$$

where $X_{50\%} = 8.52$ sec. Fifty percent of the truck drivers at the Trindle and Railroad intersection accepted a gap of 8.52 sec, and 85 percent accepted a gap of 10.06 sec. The logit model was similarly applied to the remaining combinations of vehicle and maneuver types. Table 2 presents the results from the preceding analysis.

Each intersection's unique characteristics influenced the truck driver's gap acceptance. Right-turning trucks at the Central Valley Asphalt intersection waited for the passing of platoons formed at a signalized intersection 2,000 ft upstream. Truck drivers at the Truck Stop 64 intersection frequently waited for large gaps (greater than 20 sec) that were readily available because of the low volume on the major road. Also, these drivers may have accepted larger gaps than usual, because the majority of the drivers would only accelerate for a short distance before slowing to make a turn onto Interstate entrance ramps 500 and 1,000 ft downstream. Truck drivers at the Trindle and Railroad intersection were pressured to accept smaller gaps than those accepted at the other sites. The frequency of gaps greater than 20 sec was small; long queues occasionally formed on the minor road behind the truck.

Findings from similar studies (*6,8*) for trucks and passenger cars and findings from the *Highway Capacity Manual* (*9*) for passenger cars are presented in Table 3. In 1981, Wennell and Cooper (*8*) reported on their studies conducted at five intersections in England. Data for vans and trucks were combined into an all-goods category when the data were sparse. The all-goods vehicle findings are several seconds shorter than the findings in this study. Gap lengths for passenger cars are more than 1 sec shorter than the critical gaps found in other studies and the *Highway Capacity Manual* (*9*).

Radwan et al. (*6*) conducted field studies to estimate gap acceptance distribution for drivers crossing or merging from a minor road onto a four-lane major road. Truck data for all maneuvers (right, through, and left) were combined, because the number of data points was small. The findings at the high-volume Trindle and Railroad intersection were similar to Radwan's findings for all truck maneuvers.

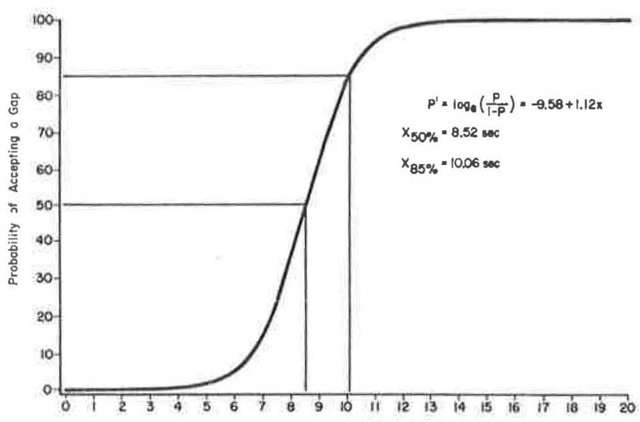

FIGURE 2 Sample logit model plot for five-axle trucks turning right at Trindle and Railroad.

Distance Gaps

Distance gap is the distance between one vehicle on the major road and the next, as the first vehicle passes the intersection (see Figure 3). The distance gap was determined at the Trindle and Railroad intersection for situations in which the vehicle was within the camera limits and was not eliminated for some other reason (such as decelerating to make a turn or entering the major road from a driveway within the study area). The distance gaps accepted, approximated to the nearest 25 ft, are presented in Table 4. Determining the distance gaps required several cameras and was only possible when the vehicle on the major road was within 500 ft of the intersection. Only 22 percent of the vehicles on the major road at the Trindle and Railroad intersection were within these camera limits.

The distance gap accepted by a vehicle on the minor road is a measure preferable to the time gap. Distance gaps are

TABLE 2 FINDINGS FROM GAP ACCEPTANCE ANALYSIS FOR TRUCKS

		Logit model at the following percent probability of accepting a gap	
Intersection	Data Sets	50 Percent (sec)	85 Percent (sec)
LEFT-TURNING 5-AXLE TRUCKS			
Central Valley Asphalt	1	--*	--
Truck Stop 64	5	--	--
Trindle and Railroad	16	8.27	9.84
RIGHT-TURNING 5-AXLE TRUCKS			
Central Valley Asphalt	0	--	--
Truck Stop 64	134	12.43	14.78
Trindle and Railroad	91	8.52	10.06
LEFT-TURNING LESS-THAN-5-AXLE TRUCKS			
Central Valley Asphalt	58	11.16	13.89
Truck Stop 64	2	--	--
Trindle and Railroad	8	--	--
RIGHT-TURNING LESS-THAN-5-AXLE TRUCKS			
Central Valley Asphalt	23	13.17	15.86
Truck Stop 64	7	--	--
Trindle and Railroad	26	7.25	8.87

*Insufficient data. Analyses were not performed for data sets containing less than 15 accepted gaps (i.e., 15 minor road vehicles).

TABLE 3 FINDINGS FROM SIMILAR STUDIES

Study	Turn Maneuvers	Gap (sec)		
		Median Accepted Gap[a]		
Wennell and Cooper, 1981*(8)*	Left turns (UK conditions)	Site	Cars	Goods[b]
		1	3.91	4.63
		3	3.66	5.33
		4	4.31	4.99
		5	4.41	4.91
		Critical Gap[c]		
Radwan, et al., 1980 multilane, divided highways*(6)*	PC, Right turns	6.73 sec		
	Trucks, all possible maneuvers	8.40 sec		
Highway Capacity Manual, 1985*(9)*		Running Speed (Major) 30 mi/h		55 mi/h
	Right turn from stop, 2 lanes	5.5 sec		6.5 sec
	Left turn from stop, 2 lanes	6.5 sec		8.0 sec

[a]Gap that has a 50 percent probability of acceptance (probit analysis).

[b]Goods category included vans and trucks when data were "sparse".

[c]Critical gap was determined using Logit model.

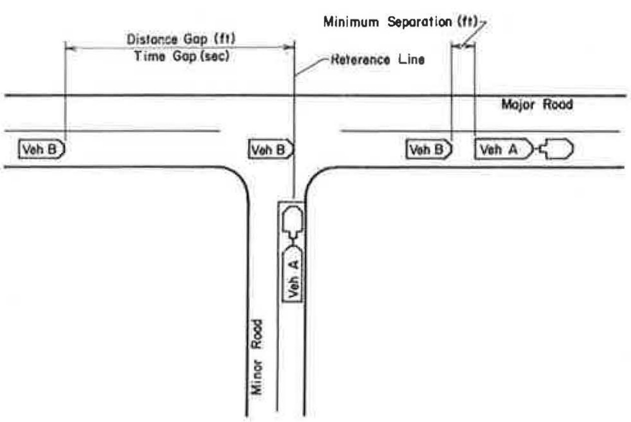

FIGURE 3 Gap and minimum separation dimensions.

directly comparable to sight distance, and time gaps can vary if a gap is accepted and the vehicle on the major road is forced to decelerate. Unfortunately, measuring distance gaps is much more difficult than observing time gaps.

Sight distances based on critical time gaps and 85th-percentile speed result in calculated sight distance values greater than the field-observed distance gap. For example, if the critical gap is 8.5 sec and the major roadway speed is 40 mph, the calculated sight distance is approximately 500 ft. A predicted distance gap from Table 4 for an 8.5-sec accepted time gap would be between 300 and 400 ft.

Acceleration

The times at which an accelerating truck left the intersection and arrived at each 100-ft increment line were read from the clock superimposed on the videotapes. These times were recorded in a computer spreadsheet program in hours, minutes, and seconds. In order to analyze the vehicles' distance-versus-time curves, the raw data were standardized so that all vehicles left the minor road at time zero.

TABLE 4 DISTANCE GAPS FOR TRUCKS AT TRINDLE AND RAILROAD

Vehicle No.	No. Axles	Time Gap (sec)	Distance Gap (ft)
RIGHT-TURNING TRUCKS, GAPS TO THE LEFT			
E 50	2	6.31	200
F 44	5	8.64	200
F 48	5	8.96	200
F 46	5	9.05	200
F 98	3	9.56	200
E 66	2	6.14	300
E 46	5	6.97	300
E 69	5	7.44	300
F 21	5	8.91	300
E 10	5	7.01	350
F 47	5	8.64	350
E 13	5	8.11	375
E 8	5	11.58	400
E 9	2	6.36	500
F 52	3	7.24	500
E 32	2	7.84	500
F 64	5	8.68	500
E 65	5	10.34	500
RIGHT-TURNING TRUCKS, GAPS TO THE RIGHT			
F 16	4	8.74	375
F 57	5	9.48	400
F 58	5	11.71	400
F 74	5	7.95	400
F 84	5	11.88	400
F 87	5	8.35	300
F 97	5	7.17	300
LEFT-TURNING TRUCKS, GAPS TO THE LEFT			
E 56	5	8.34	300
LEFT-TURNING TRUCKS, GAPS TO THE RIGHT			
E 67	2	11.55	300
F 43	5	11.67	400
F 60	5	12.13	400

Average accelerations were calculated using average velocities and average time required to traverse a given distance. Because the data were based on 100-ft increments, average speed was calculated for each 100-ft segment. Table 5 presents a summary of the average acceleration findings.

Presented in Table 6 are average acceleration rates determined from distance-versus-time plots reported by Hutton (*10*). Hutton measured the acceleration of trucks with weight-to-horsepower ratios of 100, 200, 300, and 400 lb/hp on a level and straight roadway. Table 6 also includes average acceleration rates calculated using Figure IX–22 in the Green Book (*2*). Distance and speed were taken directly from the Green Book (*2*) figure. The time required to reach a given speed or distance was calculated in 5-mph increments. The acceleration rate for a specific distance was calculated by dividing speed attained by the time required to reach the given speed.

The signalized intersection south of the Central Valley Asphalt exit did not appear to affect the acceleration behavior of the turning trucks. The calculated average acceleration rates were within the rates calculated from the Hutton curves. The median acceleration rate for trucks turning left was between Hutton's 100- and 200-lb/hp values (*10*). The median acceleration rate for right turns was near the 300-lb/hp values.

The acceleration rates at the Truck Stop 64 intersection were lower than at the other sites, because the majority of the trucks turning right eventually turned onto nearby Interstate entrance ramps. The median acceleration rate was significantly lower than those calculated at other sites. This rate was also lower than the 400-lb/hp values presented by Hutton (*10*), but it was similar to the rate calculated from AASHTO (which represents an older truck fleet with higher weight/horsepower ratios).

The median acceleration rate at the Trindle and Railroad intersection was near the value for the 100-lb/hp ratio in Table 6 for the 0- to 490-ft distances. The urbanized setting and high traffic volume on the major road influenced the acceleration rates at this site.

The rates calculated using the Green Book (*2*), Figure IX–22, were considerably lower than those of the vehicle with the poorest performance (400 lb/hp) examined by Hutton (*10*) and most rates calculated for the three study intersections. As presented in Table 6, the AASHTO acceleration rates are relatively constant (approximately 0.77 mph/sec) for the specific distances.

Deceleration

The deceleration data from the different cameras were also adjusted to a common time base. The data files from different filming days were similarly merged into three intersection files. These files were segregated by maneuver type (right or left turns). Because of the limited number of data points, the data associated with five-axle right-turning trucks at Truck Stop 64 and Trindle and Railroad intersections were combined into one data set. The number of data sets for left-turning trucks was small; therefore, only a limited analysis could be conducted.

An average speed was calculated for each 100-ft increment. These average speeds were then examined to identify where a maximum deceleration rate or speed reduction occurred. Vehicles were not considered in the analysis if they had less than a 5-mph speed reduction through the observation area or if the data displayed erratic or extreme speed variations.

The 50th and 85th percentiles for the deceleration rate and speed reduction occurring before the intersection were determined for vehicles on the major road reacting to turning five-axle trucks. These values typically represented a 200- to 400-ft total deceleration distance ending 50 to 150 ft before the intersection. Fifty percent of the vehicles impeded by five-axle trucks turning onto the major road had deceleration rates of 3.67 mph/sec or less. Eighty-five percent of the vehicles had deceleration rates of 5.85 mph/sec or less. Fifty percent of the vehicles had speed reductions of approximately 21.2 mph when impeded by five-axle trucks turning onto the road. Eighty-five percent of the vehicles had speed reductions of 38.1 mph or less.

Table 7 presents the speed reduction for each vehicle grouped by initial speed. The estimated speed reduction for each 5-mph rounded initial speed increment is also presented. The

TABLE 5 CALCULATED AVERAGE ACCELERATION RATES

Intersection	Maneuver	No. Axles	Distance (ft)	No. of Vehicles	Average Acceleration Rate (mi/h/sec) Cumulative Probability 50 Percent	85 Percent
Central Valley Asphalt	Left turn	3 & 4	0-290	25	1.27	1.58
Central Valley Asphalt	Right turn	3 & 4	0-490	8	1.04	1.21
Truck Stop 64	Right turn	5	0-350	43	0.80	1.20
Trindle and Railroad	Right turn	5	0-510	41	1.37	1.74

TABLE 6 HUTTON AND AASHTO ACCELERATION RATES (mph/sec) (*2,10*)

Distance (ft)	Hutton 100 lb/hp	200 lb/hp	300 lb/hp	400 lb/hp	AASHTO[a]
0-290	1.57	1.14	1.03	1.01	0.75
0-350	1.53	1.13	1.03	1.01	0.76
0-490	1.38	1.11	1.01	0.90	0.78
0-510	--[b]	--	--	--	0.79

[a]Values based on Green Book Figure IX-22.

[b]Data not available, curves terminate at 500 ft.

TABLE 7 SPEED REDUCTIONS FOR VEHICLES ON A MAJOR ROAD REACTING TO A FIVE-AXLE TRUCK TURNING RIGHT

Vehicle ID No.	Gap Accepted (sec)	Initial Speed (mi/h)	Speed Reductions (mi/h)	Deceleration Rate (mi/h/sec)	Rounded Initial Speed (mi/h)	Estimated Speed Reductions (mi/h)
76 F	10.78	68	40.4	7.83	70	40
116 C	18.95	64	43.2	4.46	65	35
147 C	18.45	63	29.7	6.56		
99 C	13.12	62	40.7	5.85	60	35
47 F	8.64	62	38.5	7.74		
261 C	14.65	60	36.5	3.68		
49 F	12.81	57	27.9	5.10	55	30
46 F	9.05	52	38.1	4.84	50	25
78 F	10.55	52	26.9	6.75		
84 F	11.88	52	26.1	4.37		
130 C	16.92	52	5.4	0.74		
97 F	7.17	51	17.7	2.79		
48 F	8.96	49	38.1	4.46		
57 F	9.48	49	25.1	3.85		
18 F	14.85	49	20.9	3.85		
41 F	15.90	48	21.4	3.66		
176 C	19.35	47	24.6	2.30		
17 F	13.22	46	23.0	3.56	45	20
117 C	18.55	46	17.9	2.57		
232 C	15.95	46	9.1	1.72		
201 C	14.75	45	21.5	2.25		
27 F	12.56	45	19.6	3.11		
65 E	10.34	45	18.6	4.09		
24 E	19.45	43	20.1	2.98	40	15
209 C	12.97	43	16.4	1.69		
28 E	10.81	43	15.3	4.09		
25 F	9.88	41	20.5	4.07		
30 E	15.35	41	11.9	3.23		
22 E	13.74	41	11.8	3.16		
36 F	12.98	40	14.2	2.88		
38 E	14.14	37	9.9	2.43	35	15
48 E	12.27	36	6.4	1.65		
49 E	15.61	35	19.9	3.43		

speed reductions ranged from 40 mph at a 70-mph initial speed to 15 mph at initial speeds of 40 and 35 mph.

Only limited data were available for left turns. The findings for each vehicle are presented in Table 8. A review of the findings did not reveal any differences in speed reductions or deceleration rates for vehicles in the far lane as compared with vehicles in the near lane during a left-turn maneuver. More data would be required to draw conclusions on whether drivers in the opposing lane respond differently to left-turning vehicles.

Green Book (*2*), Figure II–13, presents deceleration distances for passenger vehicles approaching intersections. The distances, which are based on comfortable deceleration rates, are determined from the speed when brakes are applied and the final speed reached. Curves are provided for the following final speeds: 50, 40, 30, 20, and 0 mph. Table 9 presents the deceleration rates based on the Green Book (*2*) figure.

Table 10 presents the observed normal deceleration rates for passenger cars on dry pavement from the *Transportation and Traffic Engineering Handbook* (*11*). The Handbook states that deceleration rates up to 5.5 mph/sec are reasonably comfortable for passenger car occupants.

The majority of the deceleration rates observed in the field are within the comfortable rates from both the Green Book (*2*) and the Handbook (*11*). Vehicles with deceleration rates greater than the Green Book (*2*) rates had initial speeds higher than 62 mph. These high-speed vehicles had to reduce their speed between 25 and 41 mph when a truck entered the traffic stream. With a 25-mph reduction, the vehicles were driving near the speed limit of the road. The speed limit and 85th-percentile speed were 40 and 51 mph at Truck Stop 64 and 40 and 40 mph at Trindle and Railroad, respectively.

Minimum Separation

The minimum separation analysis required information on both the accelerating truck and the decelerating major road vehicle. These data sets were compared to determine the number of potential minimum separation data sets available. Nine sets from the Truck Stop 64 intersection and eight sets from the Trindle and Railroad intersection were available. Two sets from each intersection were eliminated when the minimum separation location was found to be outside the camera limits. Only right-turning vehicles were selected for this analysis.

Among the various parameters estimated, the information on minimum separation was the most limited. Nonetheless, an attempt at establishing a probable range of values was made.

All time adjustments made to the acceleration and deceleration data sets (discussed in previous sections) applied to the minimum separation data sets. A plot of speed versus distance was used to estimate the location at which the vehicles were at minimum separation. A sample data set (Vehicle 99) from the Truck Stop 64 intersection is shown in Figure 4.

Minimum separation occurs when both the accelerating truck and the major-road vehicle are traveling at approximately the same speed. If the major-road vehicle is moving at a higher speed than the accelerating truck, minimum separation will occur beyond the camera's field of view. The sample major-road vehicle in Figure 4 reached its minimum speed approximately 250 ft beyond the intersection. Its speed was 11 mph, and the acceleration truck's speed was estimated at 10 mph. The headway time (t) between the vehicles was determined by finding the difference between the two vehicles' arrival times at a point 250 ft beyond the intersection. The headway

TABLE 8 DECELERATION RATES AND MAXIMUM SPEED REDUCTIONS FOR LEFT TURNS

Vehicle No.	No. Axles	Gap Accepted (sec)	Vehicle Type	Speed Reduction (mi/h)	Deceleration Rate (mi/h/sec)
TRINDLE AND RAILROAD, EASTBOUND					
36 E	3	7.78	PC	18.2	6.33
45 F	3	11.21	PC	6.3	1.94
53 F	5	9.03	PC	15.8	2.79
55 F	5	12.32	PC	18.1	2.86
56 E	5	8.34	PC	29.4	2.80
58 E	5	7.27	PC	12.6	3.25
61 E	3	11.51	PICKUP	15.2	5.37
TRINDLE AND RAILROAD, WESTBOUND					
22 F	5	15.48	PC	13.0	3.83
23 F	5	17.75	PC	15.9	4.56
31 F	5	16.59	PC	12.4	3.15
43 F	5	11.67	PC	10.7	2.18
45 F	3	11.21	PC	18.7	5.83
53 F	5	9.03	PC	13.9	3.28
56 F	5	8.24	PC	27.1	6.24
58 E	5	7.27	PC	27.7	2.53
60 F	5	12.13	PC	12.8	2.76
61 E	3	11.51	PC	21.3	3.46
CENTRAL VALLEY ASPHALT, SOUTHBOUND					
3 D	2	16.35	5-AX	13.6	3.18
7 D	3	11.35	PC	14.0	3.51
27 D	3	11.85	2-AX	26.2	5.47
30 D	2	7.81	PC	20.9	5.20

TABLE 9 DECELERATION RATES (mph/sec) FROM THE GREEN BOOK (*2*)

Initial Speed (mi/h)	Speed Reached (mi/h) 50	40	30	20	0
70	6.08	6.47	6.19	6.30	6.25
60	5.78	5.88	5.67	5.74	5.57
50		5.29	5.11	5.15	5.10
40			4.12	4.64	4.70
30				4.08	3.78
20					3.92

NOTE: Deceleration rates are based on information from Green Book Figure II-13. The rates were calculated with the following equation:

$$\text{deceleration rates} = \frac{V_f^2 - V_i^2}{2\times\text{distance}}$$

TABLE 10 DECELERATION RATES FROM THE ITE (*11*)

Speed Change (mi/h)	Deceleration rate (mi/h/sec)
15 - 0	5.3
30 - 0	4.6
40 - 30	3.3
50 - 40	3.3
60 - 50	3.3
70 - 60	3.3

NOTE: Rates are observed normal deceleration rates for passenger cars on dry pavements. Deceleration rates up to 5.5 mi/h/sec are reasonably comfortable for car occupants. (*11*)

time for the sample vehicle was 0.63 sec. The minimum separation distance can be estimated from the plots or from the following equation:

$$MS = (1.47Vt) - L \quad (4)$$

where

MS = minimum separation distance (ft),
V = velocity of turning vehicle (mph),
t = headway time between vehicles (sec), and
L = length of turning vehicle (ft).

When the calculated minimum separation distance was less than 25 ft, the minimum separation between vehicles was set at 25 ft. The minimum distance of 25 ft was selected on the basis of observations from the videotapes.

The findings for the data sets are presented in Table 11. Minimum separation between vehicles typically occurred between 200 and 400 ft downstream of the intersection. The speeds of the vehicles at minimum separation were between 10 and 24 mph at the Truck Stop 64 intersection and between 17 and 34 mph at the Trindle and Railroad intersection. These speeds are much lower than the 85th-percentile approach speeds of 51 mph for Truck Stop 64 and 40 mph for Trindle and Railroad.

The headway time between the vehicle on the major road and the turning trucks at the Truck Stop 64 intersection was 2.4 sec or less, corresponding to a minimum separation distance of approximately 25 ft. The drivers on the major road at the urban intersection of Trindle and Railroad maintained larger minimum separations. These drivers typically had 4- to 7-sec headways or 50- to 150-ft minimum separations.

The minimum separation at an urban intersection would be expected to be smaller than the minimum separation at a low-volume rural intersection. However, the values for the Truck Stop 64 intersection were lower than those obtained for the Trindle and Railroad intersection. The truck drivers at the Truck Stop 64 intersection did not accelerate as fast as the truck drivers at the urban intersection, and the running speed on the major road was also higher at the rural intersection. The results of the speed difference were that drivers on the major road closed the gap faster on trucks turning from Truck Stop 64 than on trucks turning at Trindle and Railroad. This observation was supported by the location of minimum separation at the intersections. Several of the minimum separation locations were more than 300 ft downstream from the Trindle and Railroad intersection.

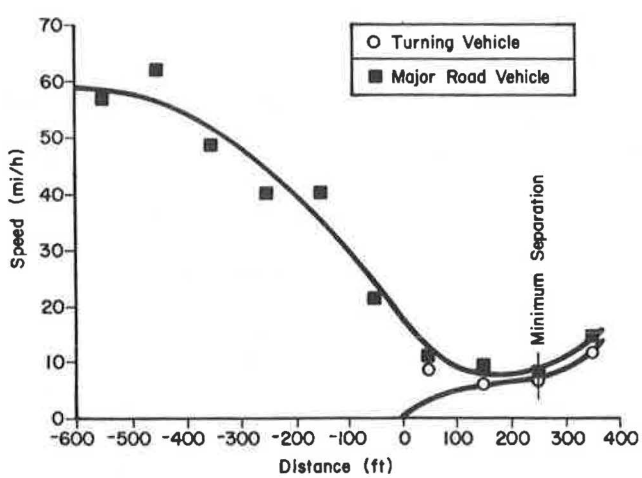

FIGURE 4 Plot of minimum separation (speed versus distance) for a sample vehicle.

The intersection sight distance criteria in the Green Book (*2*) incorporate a dimension known as "tailgate distance," which is equivalent to the minimum separation distance discussed here. However, the Green Book (*2*) does not provide guidance on the values to use for tailgate distance. When the Green Book (*2*), Figure IX-27, B-2a and Ca curve is reproduced using distance and time values approximated from Green Book (*2*), Figure IX-22, the tailgate distance, or minimum separation distance, is approximately 1 sec multiplied by the major-road speed (*12*). This figure represents the distance between the rear bumper of the turning vehicle and the front bumper of the vehicle on the major road. A 1-sec tailgate or minimum separation time represents a 15-ft minimum separation distance of 10 mph and a 30-ft distance at 20 mph.

The general findings from this limited analysis revealed a minimum separation time value of approximately 1 sec for the Truck Stop 64 intersection but higher values at the Trindle and Railroad intersection. Drivers attempted to have a larger separation distance between their vehicle and the turning vehicle if available, but they accepted 1 sec or less on some occasions.

SUMMARY OF FINDINGS

The median gaps accepted by truck drivers turning onto a major road ranged from 7.25 to 13.17 sec, depending on the intersection, turning maneuver, and truck type considered. The range of time gaps accepted with 85 percent probability was 8.87 to 15.86 sec. Table 12 presents a summary of the gaps on the basis of the logit model.

The 50th-percentile average acceleration rates ranged from 0.80 to 1.33 mph/sec, and the 85th-percentile average acceleration rates ranged from 1.20 to 1.74 mph/sec. The specific rates for the predominant truck type for left and right turns at the Central Valley Asphalt intersection and for right turns for the other two intersections are presented in Table 13.

Table 14 presents the deceleration rates and speed reductions for vehicles on the major road at the Trindle and Railroad and Truck Stop 64 intersections that were impeded by right-turning five-axle trucks. The 50th- and 85th-percentile deceleration rates were 3.67 and 5.85 mph/sec, and the speed reductions were 21.2 and 38.1 mph, respectively.

The minimum separation findings, although limited, are presented in Table 15. The headway times ranged from 0.63 to 2.38 sec at the Truck Stop 64 intersection and from 4.13 to 5.24 sec at the Trindle and Railroad intersection. The minimum separation distance between vehicles at the Truck Stop 64 intersection was assumed to be 25 ft, whereas at the Trindle and Railroad intersection the minimum separation ranged from 57 to 143 ft.

These pilot field studies are a first step toward acquisition of the data needed, either to revise the AASHTO procedures to include realistic deceleration by the vehicle on the major road, or to replace the current procedures with an alternative procedure on the basis of a gap acceptance policy.

TABLE 11 MINIMUM SEPARATION FOR FIVE-AXLE TRUCKS TURNING RIGHT

Vehicle No.	No. Axles	Gap Accepted (sec)	Headway Time (sec)	Minimum Separation Distance (ft)	Minimum Separation Time (sec)	Speed at Minimum Separation		Distance Beyond Intersection (ft)
						Major (mph)	Minor (mph)	
TRUCK STOP								
94	5	11.18	1.00	25[a]	1.55	12	11	250
99	5	13.12	0.63	25	1.89	10	9	250
116	5	18.95	2.17	25	1.89	10	9	300
130	5	16.92	1.33	25	0.81	20	21	350
147	5	18.45	1.07	25	0.74	24	23	300
176	5	19.35	2.38	25	0.81	20	21	350
209	5	12.97	0.86	25	0.71	24	24	350
TRINDLE AND RAILROAD								
22	5	13.74	5.01	109	3.22	23	23	300
24	5	19.45	4.38	91	2.69	24	23	500
28	5	10.81	4.13	143	2.95	34	33	500
38	5	14.14	4.80	88	2.85	21	21	250
45	5	10.31	4.53	57	2.15	17	18	200
59	5	8.88	5.24	75	3.00	18	17	250

[a]Minimum separation between vehicles was assumed as 25 ft based on observations from the videotapes.

TABLE 12 TIME GAPS ACCEPTED

Intersection	Turn Maneuver	Truck Type	Probability	
			50 Percent	85 Percent
Central Valley Asphalt	Left	Less-than-5-axles	11.16 sec	13.89 sec
Central Valley Asphalt	Right	Less-than-5-axles	13.17 sec	15.86 sec
Truck Stop 64	Right	Five-axle	12.43 sec	14.78 sec
Trindle and Railroad	Left	Five-axle	8.27 sec	9.84 sec
Trindle and Railroad	Right	Five-axle	8.52 sec	10.06 sec
Trindle and Railroad	Right	Less-than-5-axles	7.25 sec	8.87 sec

TABLE 13 AVERAGE ACCELERATION RATES

Intersection	Turn Maneuver	Truck Type (No. Axles)	Distance (ft)	Cumulative Probability	
				50 Percentile	85 Percentile
Central Valley Asphalt	Left	3 & 4	0-290	1.27 mi/h/sec	1.58 mi/h/sec
Central Valley Asphalt	Right	3 & 4	0-490	1.04 mi/h/sec	1.21 mi/h/sec
Truck Stop 64	Right	5	0-350	0.80 mi/h/sec	1.20 mi/h/sec
Trindle and Railroad	Right	5	0-510	1.33 mi/h/sec	1.74 mi/h/sec

TABLE 14 DECELERATION RATES AND SPEED REDUCTIONS FOR MAJOR VEHICLES ON THE MAJOR ROAD REACTING TO RIGHT-TURNING FIVE-AXLE TRUCKS

	Cumulative Probability	
	50 Percentile	85 Percentile
Deceleration Rates	3.67 mi/h/sec	5.85 mi/h/sec
Speed Reductions	21.2 mi/h	38.1 mi/h

TABLE 15 MINIMUM SEPARATION

Intersection	Headway Time (sec)	Minimum Separation Distance (ft)
Truck Stop 64	1.00	25
	0.63	25
	2.17	25
	1.33	25
	1.07	25
	2.38	25
	0.86	25
Trindle and Railroad	5.01	109
	4.38	91
	4.13	143
	4.80	88
	4.53	57
	5.24	75

SUGGESTED IMPROVEMENTS IN DATA COLLECTION AND REDUCTION METHODS

Future studies should include elevated (and concealed) video cameras. More than five cameras may be necessary for acceleration or distance gap information beyond 500 ft. Reliable and durable video equipment is necessary to minimize later adjustments to timing operations and camera coordination. Each camera's field of view should overlap the next, and each pair of cameras should include a distinguishable common reference point. An alternative approach for marking the 100-ft increment points along the approach legs is to place contrasting colored tape on the road, shoulder, or curb so that reference markings are readily discernible on the videotape. Because video cameras are sensitive to moisture and extreme ambient temperatures, primary field activities must be scheduled to avoid adverse weather conditions.

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