The Design and Performance of Safer Luminaire Supports

THOMAS C. EDWARDS (deceased), Texas Transportation Institute,
Texas A&M University

Work that has been undertaken to develop safer luminaire supports is presented. The results of 31 full-scale collision tests are summarized. These tests are grouped according to the base concept employed: steel and aluminum flanged bases, steel and aluminum transformer bases, aluminum inserts, steel progressive shear bases, notched bolts, and slip bases. Statistics for a total of 185 luminaire-support accidents are presented. These data aid in establishing the effectiveness of breakaway concepts in reducing highway injuries. A mathematical model of the vehicle-luminaire support collision is used to extend the knowledge of vehicle and support response not covered by full-scale tests. Criteria for the design of safe luminaire supports are presented.

•ACCIDENT STATISTICS have shown that roadside obstacles contribute to the majority of fatal ran-off-road accidents. Much attention has been given to means for reducing this type of accident. In some instances, relocation or elimination of obstacles can reduce the probability of fatal accidents. In most cases, however, some type of impact-limiting device can be employed, i.e., impact-attenuation devices for fixed objects and breakaway features for roadside signs and luminaire supports.

Federal agencies, state highway departments, agencies of foreign governments, and private industry have initiated projects to develop safer luminaire supports. The initial research in this area was begun in the late 1950's by the Road Research Laboratory of the Ministry of Transport in England. This work established the guideline for subsequent research and development. The guideline states that, to ensure a low impact resistance, it is necessary to incorporate some type of device at the base of the support shaft, near ground level, that will allow the support to break away in a collision but will have sufficient strength to resist static and wind-induced loads (1).

This paper is concerned with the status of the current technology in breakaway luminaire supports. The types of supports are grouped according to their breakaway base concept for the purpose of identification. A summary of the published data on full-scale collision tests of each group is given. Accident statistics are presented to aid in the evaluation of the performance of several of the concept groupings. The results of analytical studies are cited to give insight into the dynamic response of various supports. Design criteria are presented that will aid in the proper design of safer luminaire supports.

FULL-SCALE TESTS

Concept Groupings

The concepts that have been developed and tested can be classified into the following groups:

1. Flanged bases of aluminum or steel construction welded to the support shafts;
2. Frangible transformer bases of aluminum or steel construction, usually 20 in. in height and bolted to the support shaft;

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3. Frangible inserts of aluminum construction, usually 6 in. in height, used in conjunction with flanged bases or steel transformer bases;
4. Progressive shear bases of carbon steel or stainless steel construction, bolted or slip-fitted to the support shaft;
5. Notched bolts of steel construction with a necked-down section in the bolt shank; and
6. Slip bases of steel construction with slotted base plates restrained by clamping bolts.

Summary of Full-Scale Tests

Table 1 gives the pertinent results of full-scale, head-on collision tests that have been conducted and reported in the literature. Three parameters can be used as a measure of the severity of the collision: the change in vehicle velocity, ΔV, the change in momentum or impulse, ΔM, and the vehicle deformation, d. The change in velocity of the vehicle reflects the velocity of an unrestrained passenger relative to the vehicle. If it is assumed that the passenger will strike the interior of the vehicle with this velocity, then a tolerable upper limit can be established from biomedical data. Patrick has indicated that the upper limit for head and chest injuries is 11 mph (2). If this criterion is used, the concepts that could have caused passenger injury are given in Table 2 along with the corresponding momentum change and vehicle deformation.

Change in momentum can be considered as a weighted velocity change (ΔM = vehicle mass × change in velocity). The U.S. Bureau of Public Roads has recommended 1,100 lb/sec as an acceptable value. This value is well below the value given in Table 2. Vehicle deformation is a measure of the collision force but is not a definite measure of

TABLE 1

SUMMARY OF FULL-SCALE TESTS OF LUMINAIRE SUPPORTS

Concept	Pole	Test	Reference	Shaft (ft)	W_V (lb)	V_i (mph)	V_f (mph)	ΔV (mph)	ΔM (lb/sec)	d (in.)	Vehicle
1. Flange base											
a. Steel	Steel	1075-11	5, pp. 9, A-10		3,600	40.5	29.2	11.3	1,853	27.4	1958 Ford
b. Aluminum	Aluminum	1075-10	5, pp. 12, A-9		3,500	44.0	37.2	6.8	1,084	23.1	1957 Ford
c. Aluminum	Aluminum	538-4	6, p. 160	37.2	3,700	37.7	28.3	9.4	1,584	15.0	1958 Ford
d. Aluminum	Aluminum	538-11	6, p. 172	37.2	3,580	40.8	33.7	7.1	1,158	12.4	1958 Ford
e. Aluminum	Aluminum	538-5	6, p. 191	28.0	3,820	42.2	38.2	4.0	696	9.1	1958 Ford
f. Aluminum	Aluminum	193	7, p. 8	28.5	4,540	38.2	34.6	3.6	744	19.0	1966 Dodge
g. Fiber glass		1075-7	5, pp. 24, A-7	40.0	3,600	55.8	53.3	2.5	410	3.0	1958 Ford
2. Transformer base											
a. Steel	Steel	1075-12	5, pp. 9, A-11	40.0	3,700	39.4	0.0	39.4	6,640	30.0	1958 Ford
b. Aluminum	Steel	1075-3	5, pp. 14, A-3	40.0	3,460	22.2	17.8	4.4	693	12.1	1959 Ford
c. Aluminum	Steel	1075-4	5, pp. 14, A-4	40.0	3,700	44.8	41.5	3.3	556	15.5	1959 Ford
d. Aluminum	Steel	1075-6	5, pp. 14, A-6	40.0	2,140	45.7	38.0	7.7	751	12.3	1960 Simca
e. Aluminum	Steel	538-6	6, p. 116	35.0	3,580	43.8	36.7	7.1	1,158	14.0	1958 Ford
f. Aluminum	Steel	538-13	6, p. 125	35.0	3,340	39.5	32.5	7.0	1,065	16.0	1958 Ford
g. Aluminum	Steel	197	7, p. 9	28.6	4,540	15.8	0.0	15.8	3,267	21.0	1966 Dodge
h. Aluminum	Aluminum	1075-9	5, pp. 17, A-8	40.0	3,680	21.3	17.0	4.3	721	10.9	1959 Ford
i. Aluminum	Aluminum	1075-5	5, pp. 17, A-5	40.0	3,600	43.2	38.0	5.2	853	10.2	1957 Ford
3. Insert, 6 in.											
a. Aluminum with steel transformer base	Steel	1075-1	5, pp. 20, A-1	30.0	3,460	32.2	27.3	4.9	772	14.4	1955 Ford
b. Aluminum with steel transformer base	Steel	1075-2	5, pp. 20, A-2	30.0	3,580	53.2	47.0	6.2	1,011	15.8	1955 Ford
c. Aluminum without steel transformer base	Steel	182	7, p. 3	28.5	4,540	39.7	35.6	4.1	848	12.5	1966 Dodge
d. Aluminum modified without steel transformer base	Steel	191	7, p. 4	28.5	4,540	47.7	45.2	2.5	517	12.0	1966 Dodge
4. Progressive shear base											
a. Stainless steel		538-7	6, p. 143	35.4	3,880	43.1	35.3	7.8	1,378	16.0	1958 Ford
b. Carbon steel transformer base		538-8	6, p. 152	37.0	3,620	44.0	37.3	6.7	1,105	15.0	1958 Ford
5. Notched bolt											
a. Stainless steel, H-1050 deg	Steel	192	7, p. 6	28.5	4,540	39.9	38.0	1.9	393	2.0	1966 Dodge
b. Stainless steel, H-1050 deg		194	7, p. 7	28.5	4,540	14.8	0.0	14.8	3,061	21.0	1966 Dodge
6. Slip base											
a. Cambridge	Steel		4, p. 24	40.0	2,400	62.0	60.0	2.0	219	9.0	Hillman
b. TTI triangular	Steel	195	7, p. 10	28.5	4,540	40.4	39.0	1.4	207	9.0	1966 Dodge
c. TTI triangular	Steel	196	7, p. 10	28.5	4,540	15.8	14.8	1.0	207	3.0	1966 Dodge
d. TTI triangular	Steel	538-10	6, p. 200	35.0	3,340	27.6	23.4	4.2	636	9.0	1958 Ford
e. TTI triangular	Steel		8, p. 7	35.0	3,640	40.6	37.7	3.3	481	9.0	1958 Ford
f. TTI triangular	Steel	1075-S2	9, p. 12	40.0	3,400	38.3	35.9	2.4	372	—	1959 Ford
g. TTI triangular	Steel	1075-S3	9, p. 12	40.0	3,500	35.7	34.0	1.7	271	—	1957 Ford

Note: W_V = vehicle weight, V_i = vehicle velocity at contact, V_f = vehicle velocity at rear tapeswitch set, ΔV = change in vehicle velocity, ΔM = change in momentum, and d = vehicle deformation.

TABLE 2

PROBABLE INJURY COLLISIONS

Concept	ΔV (mph)	ΔM (lb/sec)	d (in.)
1a. Steel flange base	11.3	1,853	27.4
2a. Steel transformer base	37.4	6,640	30.0
2g. Aluminum transformer base	15.8	3,267	21.0
5b. Stainless steel notched bolt	14.8	3,061	21.0

collision severity because of the variability in vehicle construction. In any event, these indicators appear to be related.

Data given in Table 1 from the tests that were run at high and low velocity (concepts 2, 5, and 6) indicate that the collision response is a function of velocity for concept groups 2, transformer base, and 5, notched bolts. This effect is not as evident in concept group 5, slip base.

From the results of the full-scale tests it can be concluded that, for head-on collisions, all concept groups except the steel flanged base and the steel transformer base effectively limit collision forces when hit at velocities in excess of 25 mph. However, at velocities lower than this, all concept groups except the slip base are capable of producing injury accidents.

Criteria for Safe Collision Response

For the following development, it must be assumed that the safe change in vehicle velocity is 11 mph (this is the relative velocity at which passenger contact with the interior of the vehicle will not cause injury). The impulse that indicates safe response is

$$I = \frac{W}{g} (\Delta V) = \frac{W}{32.2} (11)(88/60) = \frac{W}{2} \text{ (lb/sec)}$$

where

I = impulse (lb/sec),
W = vehicle weight (lb),
ΔV = velocity change (fps), and
$I = \frac{\text{vehicle wt}}{2}$ (lb/sec).

From the impulse-momentum principle,

$$I = W\, g_{avg}\, \Delta t$$

where

g_{avg} = average deceleration (g units), and
Δt = duration of collision event (sec).

Then

$$g_{avg} = I/W\Delta t = \frac{(W/2)}{W\Delta t} = \frac{1}{2\Delta t} \text{ (g units)}$$

The safe average and peak g for various collision durations are as follows:

Δt (sec)	g_{avg}	g peak
0.025	20.0	31.4
0.050	10.0	15.7
0.100	5.0	7.9
0.150	3.3	5.2
0.200	2.5	4.0

where

Δt = duration of collision event, and
g peak = $(\pi/2)\, g_{avg}$ (based on sinusoidal pulse).

ACCIDENT STATISTICS

The performance of a luminaire support in actually reducing roadside collision injuries should be weighed heavily in evaluating a particular concept. The very limited amount of accident information available supports the premise on which present design is based.

TABLE 3

EFFECT OF BASE AND POLE TYPES ON INJURIES

Base and Pole Type	No. of Accidents	Injuries				Total Injuries	Injury Accidents	Percent Injury Accidents
		Type A[a]	Type B[b]	Type C[c]	Type O[d]			
Base								
Aluminum transformer	77	5	4	9	59	18	17	22
Steel transformer	37	12	3	5	17	20	18	49
Aluminum steel and flange	35	14	9	0	12	23	16	46
Total	149	31	16	14	88	61	51	
Installation								
Aluminum pole with aluminum transformer base	58	2	4	7	45	13	12	21
Steel pole with aluminum transformer base	19	3	0	2	14	5	5	26
Total	77	5	4	9	59	18	17	

[a]Visible signs of injury or bleeding wound or distorted member or had to be carried from scene.
[b]Other visible injury, such as bruises, abrasions, swelling, or limping.
[c]No visible injury, but complaint of pain or momentary unconsciousness.
[d]No injury indicated.

Lazenby studied a total of 149 accident reports (3). These accidents were from rural and urban locations in several widely separated parts of Texas. Seventy-seven of these accidents involved supports with aluminum transformer bases (concept group 2); 37 involved steel transformer bases (concept group 2a); and 35 involved flanged bases (concept group 1). Table 3 gives the findings (3, pp. 25, 26).

Collisions with rigidly mounted supports, i.e., steel transformer bases and steel and aluminum flange bases, are much more severe than those with the supports mounted on aluminum transformer bases. In general, collisions with more rigid supports produce twice as many injury accidents on a percentage basis. The data given in Table 3 indicate the influence of support mass on the collision severity. One cannot draw any far-reaching conclusions from these data; however, they do indicate that the presence of a breakaway base has a much more significant influence on the collision severity than does the support mass (this assumes that all supports in the study were of conventional mounting height).

Another study conducted by the author supplies additional information on the performance of supports mounted on aluminum transformer bases and flange bases. The statistics used in this study were obtained from accidents on urban expressways in one large Texas city. Table 4 gives the results of the study. These statistics along with those compiled by Lazenby clearly indicate that a breakaway base can function effectively in reducing the severity of accidents.

An interesting observation can be made from the data given in Table 4. Of the 22 accidents involving the aluminum transformer base and mounting height under 30 ft, 15 were frontal collisions with only one injury and 7 were side collisions with 3 injuries. Of the 6 collisions with the aluminum transformer base and mounting height over 30 ft, 3 were frontal collisions involving 1 injury and 3 were side collisions involving 2 injuries. All of the collisions involving flange bases were frontal. These figures indicate that, although breakaway bases are adequate in reducing injuries from frontal collisions,

TABLE 4

EFFECT OF BASE TYPE ON INJURIES FROM FRONTAL AND SIDE COLLISIONS

Mounting Height and Base Type	No. of Accidents	Injuries				Frontal Collision			Side Collision		
		Type A[a]	Type B[b]	Type C[c]	Type O[d]	Type A	Type B	Type O	Type A	Type B	Type O
Between 0 and 30 ft											
Aluminum transformer base	22	3	1	0	18	1	0	14	2	1	4
Aluminum flange base	8	5	0	0	3	5	0	3	0	0	0
Total	30	8	1	0	21	6	0	17	2	1	4
Between 30 and 44 ft											
Aluminum transformer base	6	3	0	0	3	1	0	2	2	0	1
Aluminum flange base	0	0	0	0	0	0	0	0	0	0	0
Total	6	3	0	0	3	1	0	2	2	0	1

[a]Visible signs of injury or bleeding wound or distorted member or had to be carried from scene.
[b]Other visible injury, such as bruises, abrasions, swelling, or limping.
[c]No visible injury, but complaint of pain or momentary unconsciousness.
[d]No injury indicated.

TABLE 5
REPRESENTATIVE BASE FRACTURE ENERGIES

Concept	Place Hit	Base Fracture Energy (ft-lb)
Aluminum flange base	—	11,000
Aluminum transformer base	Normal to flat face	9,000
Progressive shear carbon steel transformer base	Normal to flat face	15,000
Slip base, TTI triangular with	On corner	7,500
2,000-lb bolt preload	—	750

there is a possibility that injuries can be produced when the vehicle strikes the support in a broadside attitude.

ANALYTICAL INVESTIGATIONS

An analytical study was conducted by the Texas Transportation Institute in which a mathematical model of the luminaire support-vehicle collision was formulated (6, p. 279). Typical results from this study are shown in Figures 1 and 2.

These figures relate the change in vehicle velocity to the type of support, the energy required to fracture or activate the breakaway base, the vehicle weight, and the collision velocity. Collisions that fall to the right of the shaded zone indicate that the support shaft will not fall on the vehicle; collisions that fall to the left indicate that the support shaft will contact the vehicle in the passenger compartment area. Collisions that fall within the shaded zone indicate probable pole-vehicle contact. These figures substantiate the findings from the full-scale tests; i.e., supports with high base fracture energy produce the greatest velocity change, and the most severe collision occurs at low vehicular collision velocities. Representative base fracture energies of several of the base concept groupings determined from laboratory tests are given in Table 5 (these are nominal values and may vary for different manufacturer's designs) (6, p. 237).

Figure 3, developed using the mathematical model, shows that the maximum translation of the fallen support toward the roadway occurs in low-velocity collisions in which the mast arm end, R, comes to rest near the pavement edge. For higher velocity

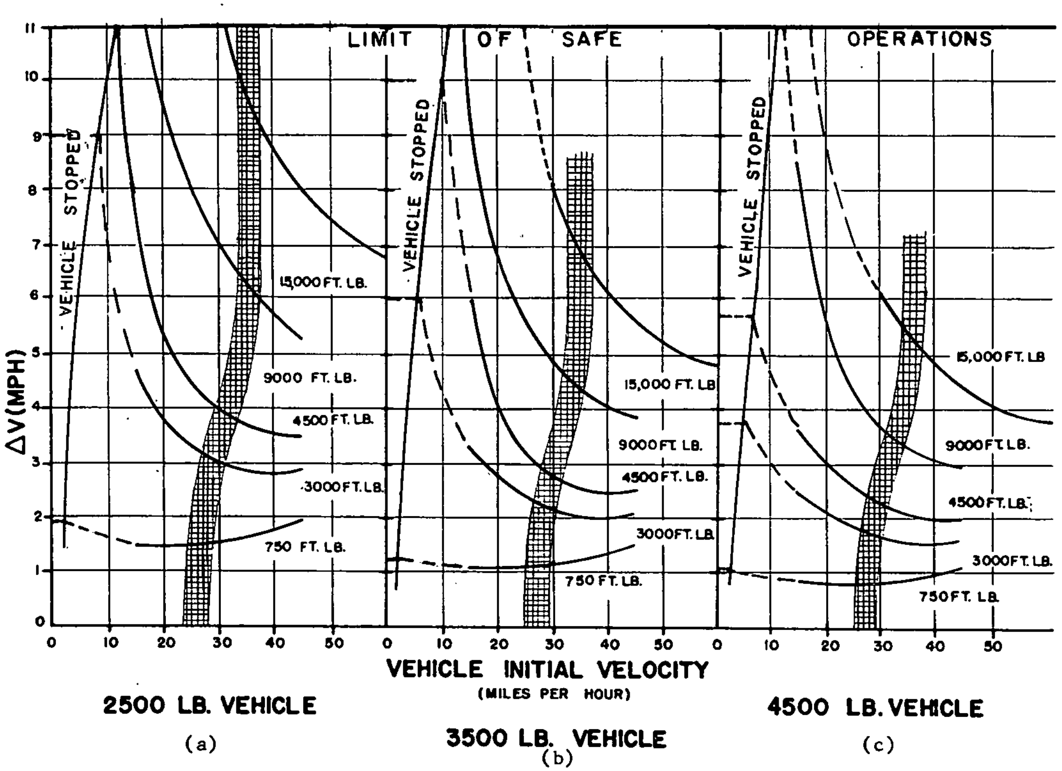


Figure 1. Aluminum support with 40-ft mounting height.

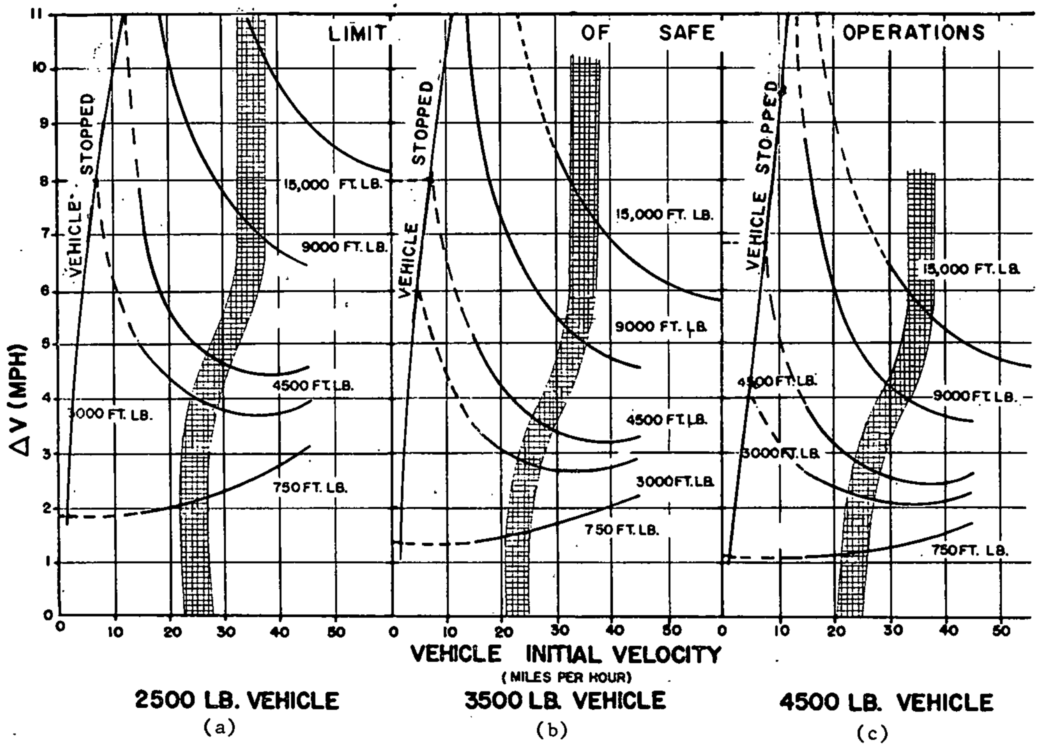
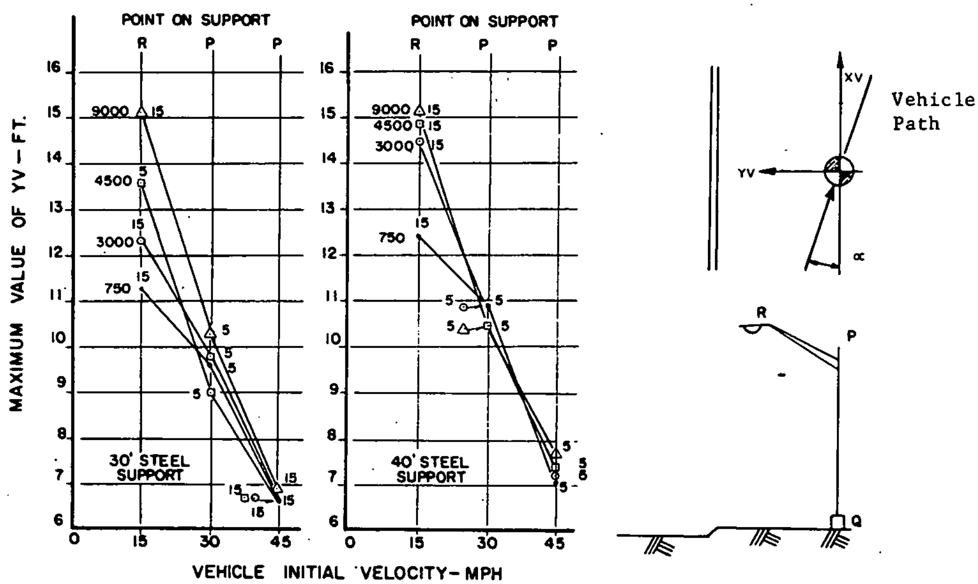


Figure 2. Steel support with 40-ft mounting height.



Numbers by points indicate the angle α

Figure 3. Maximum translation of fallen steel supports.

TABLE 6

MINIMUM COLLISION VELOCITY FOR BASE FRACTURE ENERGY GREATER THAN THAT FOR SAFE COLLISION AT 11 MPH

Vehicle Weight (lb)	Base Fracture Energy (ft-lb)	Velocity (mph)
2,500	9,000	18
	15,000	35
3,500	9,000	14
	15,000	23
4,500	9,000	13
	15,000	18

collisions the support rotates clockwise, viewed from the top, and hence the mast arm is directed away from the pavement edge such that the top of the pole, P, falls nearest the pavement edge. This phenomenon has been observed in many full-scale crash tests as well as in roadside accidents.

EVALUATION OF SUPPORTS FOR SAFE PERFORMANCE

Figures 1 and 2 can be used to evaluate existing test procedures as well as to aid the development of design criteria. Most full-scale tests in current programs are conducted at moderate velocities (40 mph). Note from the figures that this velocity does not reflect the true collision severity because of the rapid reduction of vehicle response at the higher velocities. A more realistic appraisal of a particular design results if tests are conducted at velocities that yield vehicle velocity changes near the velocity change threshold of 11 mph. For example, in Figure 1, a collision of a 2,500-lb vehicle at 40 mph with a support base having a base fracture energy of 1,500 ft-lb yields a velocity change of 8.8 mph, an acceptable value. However, if the same support is hit at 30 mph, a velocity change in excess of 11 mph will result. This would be a possible injury collision. In order that any design may be evaluated, the base fracture energy of the base must be known. This can be established by laboratory tests.

The limits on the base fracture energy are determined by the condition when the vehicle is brought to a complete stop with a collision velocity of 11 mph. This can be determined by the point where the base fracture energy curve intersects the 11-mph velocity change (ΔV) line. For the aluminum support mounted 40 ft high, shown in Figure 1, these values are 4,500 ft-lb for the 2,500-lb vehicle, approximately 6,500 ft-lb for the 3,500-lb vehicle, and approximately 8,000 ft-lb for the 4,500-lb vehicle. The results are approximately the same for the steel support mounted 40 ft high shown in Figure 2. The following are maximum base fracture energies by which safe collision performance can be expected for all weight vehicles at a minimum collision velocity of 11 mph:

Vehicle Weight (lb)	Base Fracture Energy (ft-lb)
2,500	4,500
3,500	6,500
4,500	8,000

As shown in the figures, higher base fracture energies impose collision velocity limits. Table 6 gives these values.

DESIGN CRITERIA

The results of accident studies, full-scale collision tests, and the analytical model have been used to develop design criteria (6, p. 72). The criteria are formulated such that proposed designs can be checked for safe performance. The criteria can be stated as follows:

1. Frangible and progressive shear bases should be of such height as to allow the vehicle bumper to contact them rather than the luminaire support shaft.
2. The base fracture energy of the breakaway base, as determined from laboratory impact tests, can be used as a measure of energy absorbed by the base in a full-scale collision.
3. Any type of base whose base fracture energy is dependent on its orientation should be placed so that the most probable collision angle coincides with the direction of least resistance.

4. When luminaire supports must be located in places where the probability of low-velocity collisions is high, support bases should have the lowest possible fracture energy and the support poles should be constructed of lightweight materials.

5. Under most conditions, the luminaire support after a collision will assume a longitudinal position approximately parallel to the vehicle path with the top of the pole displaced laterally toward the roadway. The probability of encroachment of the shaft into the traveled lanes is greatest for low-velocity collisions (15 mph). At collision velocities above 30 mph, the lateral displacement decreases and, in normal circumstances, no encroachment should occur. The danger that the support presently in use will fall into the traveled lanes is small if it is located at a distance from the pavement edge equal to or greater than the mast arm length.

6. In collisions with velocities of 40 mph or greater, supports with mounting heights of 40 ft or less and with bases that exhibit base fracture energies of approximately 9,000 ft-lb will clear the vehicle.

7. A collision speed of 35 mph appears to be the lower limit at which one can expect a conventional support with a mounting height of 30 to 40 ft to clear the vehicle or hit behind the passenger compartment.

8. Large supports with mounting heights of 50 ft or greater and with base fracture energies in excess of 9,000 ft-lb should be considered with caution because low-velocity collisions may be severe and most likely will result in passenger injury.

CONCLUSIONS

The following conclusions can be drawn from the review of the technology presented in this paper:

1. The severity of a vehicular collision with a luminaire support having a conventional mounting height is primarily dependent on the collision velocity and the energy required to fracture the base of the support. The support and the vehicle mass are of lesser importance and exert an influence only with supports of larger mounting heights.

2. For head-on collisions, all concepts except the steel flange base and the steel transformer base effectively limit collision forces when hit at velocities in excess of 25 mph. At velocities below this, all concepts except the slip bases are capable of producing injury accidents. Accident statistics indicate that broadside collisions with aluminum transformer and aluminum flange base supports can produce injuries.

3. The results of analytical studies have shown that analytical investigative techniques can be used effectively to study support and vehicle response to collisions.

ACKNOWLEDGMENT

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