Effect of Cargo Displacement on Vehicle Collision Behavior

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The potential for rollover after a vehicle has collided with a roadside barrier is greatest for vehicles that have a high center of gravity, such as school buses, intercity buses, and trucks. There are various computer programs that can simulate vehicle-barrier interaction, but they can be expensive to run and do not address the phenomenon of cargo displacement during vehicle impact with a roadside barrier. A computer program that can be used to estimate the effect of cargo displacement on secondary-impact vehicle roll response is described. It is applied to delineate the rollover potential of a school bus carrying unrestrained children during a collision with a highway barrier.

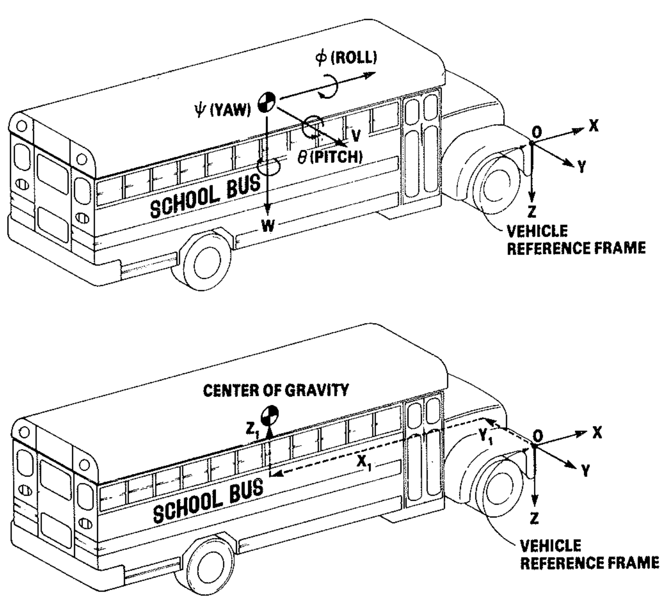
The rollover vaulting algorithm (RVA) (1) is a simple tool for evaluating the potential for vehicle rollover after collision with a highway barrier. In the RVA program, the single-unit vehicle is a 6-df model acted on by barrier-induced forces and tire-suspension reaction forces (Figure 1). Both vehicle and barrier are assumed to be nondeformable where the barrier is a vertical plane.

In RVA, the vehicle-barrier interaction takes place in three phases: (a) the initial impulsive impact with the barrier; (b) a continuous, nonimpulsive translational and rotational motion during redirection; and (c) a second impulsive impact when the rear of the vehicle swings around and strikes the barrier. Although the program provides insight into rollover potential, it, like other available vehicle-barrier models, precludes consideration of postimpact cargo movement during vehicle redirection. The RVA program was therefore modified in an effort to define the effect of cargo shift on vehicle performance.

Recently, an experimental test was conducted at Southwest Research Institute (SwRI) that involved the collision of a 9100-kg (20 000-lb) school bus with a flexible barrier at a speed of 97 km/h (60 miles/h) and an angle of 15°. The collision resulted in vehicle rollover. Sandbags positioned in the vehicle seats were used to simulate unrestrained children. The vehicle's center of gravity (including sandbags) was located 1.17 m (46 in) above the roadway, and the barrier height was 0.89 m (35 in). This relatively low center of gravity with respect to barrier height did not suggest a potential rollover problem. However, a film-analysis comparison with an earlier test performed by the Texas Transportation Institute showed that, after the bus redirected, significant sandbag displacement occurred as the rear section of the bus hit the barrier (at t = 0.6 s in Figure 2).

The decision to modify the original RVA computer program was based on the results of this full-scale test. The objective was to verify or refute the belief that the sandbag displacement during impact was a primary cause of vehicle rollover.

Figure 1. RVA vehicle model.



SPECIFIC PROGRAM MODIFICATIONS

Input Data

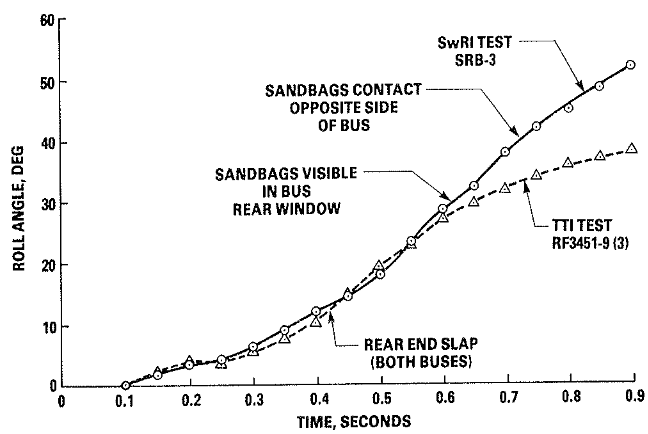
In the original RVA computer program (1), the user inputs the vehicle properties, including location of center of gravity; vehicle length, width, and height; and suspension properties with respect to a fixed reference frame such as that shown in Figure 1. These data remain the same in the modified version, RVA 2. The additional input requirements for the RVA 2 program are simply total cargo weight, initial position of the cargo center of gravity (x_2, y_2, z_2) with respect to the vehicle reference frame (x, y, z), and assumed displaced position of the cargo center of gravity (x_2', y_2', z_2') after secondary vehicle impact.

Computation of Center of Gravity

The additional input data are used in the program to estimate the change in the position of the vehicle's overall center of gravity and inertial properties because of cargo displacement. In RVA 2, the altered center of gravity is readily located by applying the theory of parallel forces. The vehicle center of gravity is first determined with the cargo excluded, i.e.,

$$x_1' = (W_v x_1 - W_C x_2)/(W_v - W_C) \quad (1)$$

Figure 2. Effect of sandbag displacement on roll angle.



$$y_1' = (W_v y_1 - W_C y_2)/(W_v - W_C) \quad (2)$$

$$z_1' = (W_v z_1 - W_C z_2)/(W_v - W_C) \quad (3)$$

where

x_1, y_1, z_1 = initial vehicle center-of-gravity coordinates including cargo,
x_1', y_1', z_1' = initial vehicle center-of-gravity coordinates with cargo removed,
W_v = total vehicle weight including cargo, and
W_C = total cargo weight.

By using an assumed displaced-cargo position (x_2', y_2', z_2'), the location of the altered vehicle center of gravity ($\tilde{x}_1$, $\tilde{y}_1$, $\tilde{z}_1$) at the instant of secondary impact is evaluated as follows:

$$\tilde{x}_1 = (1/W_v)\,[(W_v - W_C)x_1' + W_C x_2'] \quad (4)$$

$$\tilde{y}_1 = (1/W_v)\,[(W_v - W_C)y_1' + W_C y_2'] \quad (5)$$

$$\tilde{z}_1 = (1/W_v)\,[(W_v - W_C)z_1' + W_C z_2'] \quad (6)$$

where the RVA 2 program uses Equations 1-3 in conjunction with Equations 4-6.

Reevaluation of Vehicle Inertia Matrix

In the original RVA program (1), the moment-of-inertia matrix (e.g., I_{ij}) with respect to the vehicle center of gravity is evaluated in relation to the fixed-body coordinate system (I^o_{ij}) through application of the fundamental parallel-axis theorem. In RVA 2, the parallel-axis theorem is also applied to evaluate the effect of cargo displacement on the vehicle inertia matrix.

The RVA 2 program evaluates the expressions of cargo inertia in relation to the vehicle-body fixed reference frame (x, y, z) with the cargo in its original (x_2, y_2, z_2) and displaced (x_2', y_2', z_2') positions. Since the cargo is displaced within the confines of the vehicle, the analysis does not require an evaluation of the cargo-inertia matrix with respect to the cargo center of gravity.

In the program logic, the initial cargo-inertia matrix (with respect to the vehicle reference frame) is evaluated and subtracted from the overall vehicle-inertia matrix. The inertia matrix of the displaced cargo in relation to the vehicle system is then added. The newly defined vehicle-inertia matrix is called in RVA 2 after the vehicle has redirected and secondary impact is imminent. At present, this computer flag assumes cargo translation when the yaw angle between the longitudinal centerline of the vehicle and the horizontal axis of the barrier is less than 3° (program logic precluded the use of a zero yaw angle to affect the cargo displacement). Although cargo displacement may occur to some degree after the initial impact, the SwRI full-scale test did not demonstrate significant displacement until secondary impact occurred. The updated center-of-gravity location and vehicle-inertia matrix are input into the original RVA energy equations (Equations 1-3) after the secondary impact to determine whether the resulting angular velocity is sufficient to cause vehicle rollover.

SIMULATION FINDINGS

The decision to modify the RVA program (1) was based, in part, on the recent SwRI full-scale test with a school bus. As a result, 12 initial simulations were performed in which a 9100-kg (20 000-lb) school bus was modeled interacting with 0.89-, 0.84-, and 0.76-m (35-, 33-, and 30-in) high rigid vertical barriers (see Table 1). An impact speed of 92 km/h (57 miles/h) and an approach angle of 17.5° were used in all 12 simulations. With the exception of cargo weight and position, all of the input vehicle properties (e.g., inertia matrix) were based on actual measurements obtained from the test vehicle. These corresponded to the actual test conditions.

For the first three simulations (cases 1, 2, and 3), the effect of cargo shift was excluded by inputing a zero cargo weight. According to the critical roll rate, which is defined in RVA and RVA 2 as the minimum roll angular velocity for rollover, these three simulations did not suggest a rollover problem. In the next series of simulations (cases 4, 5, and 6), a 2700-kg (6000-lb) cargo was used [total vehicle weight maintained at 9100 kg (20 000 lb)], and the cargo initial center-of-gravity position coincided with the center of gravity. Although this cargo position is an unlikely situation, these simulations were performed because

Table 1. Rollover potential of school bus.

Case	Barrier Height (m)	Vehicle Center of Gravity[a] (m) x_1	y_1	z_1	Cargo Position (m) Original x_2	y_2	z_2	Displaced x_2'	y_2'	z_2'	Post-Secondary-Impact Roll Rate: Positive Toward Barrier (°/s)	Percentage of Critical Rate
1[b]	0.89	-5.39	-1.22	-0.28	-5.39	-1.22	-0.28	-5.39	0	-1.04	57.1	33
2[b]	0.84	-5.39	-1.22	-0.33	-5.39	-1.22	-0.33	-5.39	0	-1.09	64.3	38
3[b]	0.76	-5.39	-1.22	-0.41	-5.39	-1.22	-0.41	-5.39	0	-1.17	101.0	63
4	0.89	-5.39	-1.22	-0.28	-5.39	-1.22	-0.28	-5.39	0	-1.04	88.3	64
5	0.84	-5.39	-1.22	-0.33	-5.39	-1.22	-0.33	-5.39	0	-1.09	107.8	80
6	0.76	-5.39	-1.22	-0.41	-5.39	-1.22	-0.41	-5.39	0	-1.17	140.8	110
7	0.89	-5.39	-1.22	-0.28	-5.39	-1.22	-0.28	-6.15	0	-1.04	94.7	68
8	0.84	-5.39	-1.22	-0.33	-5.39	-1.22	-0.33	-6.15	0	-1.09	114.6	84
9	0.76	-5.39	-1.22	-0.41	-5.39	-1.22	-0.41	-6.15	0	-1.17	147.7	113
10	0.89	-5.39	-1.22	-0.28	-5.39	-1.22	-0.28	-5.39	0	-1.30	94.0	73
11	0.89	-5.39	-1.22	-0.28	-5.39	-1.22	-0.28	-5.39	0	-1.55	97.1	82
12	0.89	-5.39	-1.22	-0.28	-5.39	-1.22	-0.28	-5.39	0	-1.80	98.2	90

Notes: 1 m = 3.3 ft; 1 $m \cdot kg \cdot s^2$ = 0.0115 $in \cdot lb \cdot s^2$.
Vehicle was a 9100-kg school bus, for which speed = 92 km/h, angle = 17.5°, center of gravity = 1.17 m above the roadway, cargo weight = 2700 kg, roll = 495 $m \cdot kg \cdot s^2$, pitch = 9165 $m \cdot kg \cdot s^2$, and yaw = 9124 $m \cdot kg \cdot s^2$.

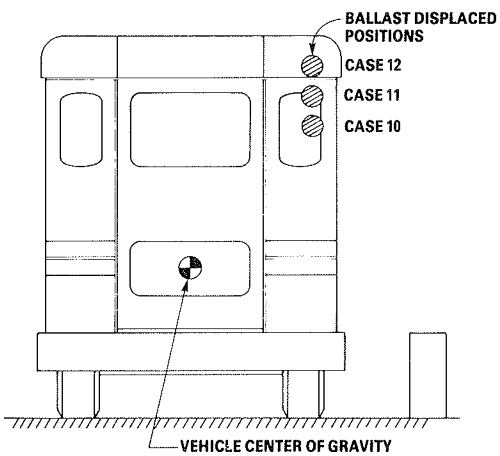
[a] Locations in vehicle fixed reference frame (x, y, z) with origin at barrier-vehicle contact point (Figure 1).

[b] Zero cargo used.

they are analogous to what is indirectly assumed with existing vehicle-barrier computer programs when a single center of gravity is delineated. At secondary impact, the cargo was assumed to be displaced 1.22 m (48 in) laterally (to the vehicle interior side wall) and 0.76 m (30 in) vertically (above the center of gravity). The results, given in Table 1, indicate a significant increase in post-secondary-impact roll rate, particularly in case 6, where the bus rolled over the barrier (i.e., 110 percent of critical roll rate).

The effect of a longitudinal cargo displacement on vehicle rollover potential was considered in cases 7, 8, and 9. For these simulations, the assumed displacement was 1.22 m (48 in) laterally, 0.76 m (30 in) vertically (upward), and 0.76 m (30 in) longitudinally (rearward). The findings demonstrated only minor effects on rollover potential.

Figure 3. Typical assumed positions of displaced cargo.



Simulations 10, 11, and 12 involved the 0.89-m (35-in) high barrier. In these three cases, the cargo was also displaced to the vehicle side wall. However, for each simulation, a different (displaced) cargo position above the vehicle center of gravity was imposed (see Figure 3). As Table 1 indicates, when the cargo was displaced 1.27 and 1.52 m (50 and 60 in) above the vehicle center of gravity, the resulting roll velocities reached 82 and 90 percent of the estimated critical roll values, respectively. These are substantially higher values than those that resulted from the simulation in which the cargo was not considered (case 1).

All 12 simulations assumed an initial cargo location at the vehicle center of gravity and either a 0- or 2700-kg (6000-lb) cargo. Test-vehicle measurements defined a cargo weight of 3200 kg (7100 lb) and a center-of-gravity location as shown in Figure 4. These data were used in three additional simulations. Results with the cargo weight and position included are given in Table 2. When the cargo was displaced 1.52 m (60 in) above the vehicle center of gravity (at the side wall), the hazardous rollover mode occurred (case 15). The significance of this finding is realized when roll-rate results

Figure 4. Cargo location in full-scale test.

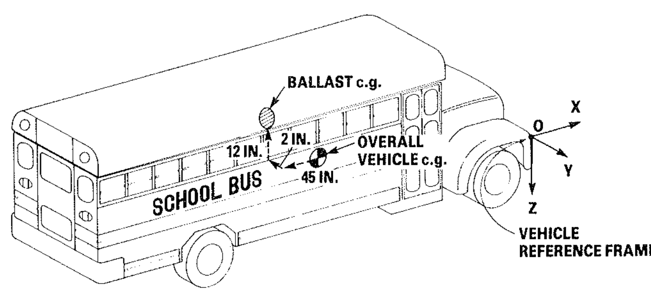


Table 2. School-bus simulations with 3200-kg cargo.

				Cargo Position (m)						Post-Secondary-Impact Roll Rate	
	Vehicle Center of Gravity[a] (m)			Original			Displaced			Positive Toward Barrier (°/s)	Percentage of Critical Rate
Case	x_1	y_1	z_1	x_2	y_2	z_2	x_2'	y_2'	z_2'		
13	-5.39	-1.22	-0.28	-6.53	-1.27	-0.58	-6.53	0	-1.30	96.5	76
14	-5.39	-1.22	-0.28	-6.53	-1.27	-0.58	-6.53	0	-1.55	103.6	89
15	-5.39	-1.22	-0.28	-6.53	-1.27	-0.58	-6.53	0	-1.80	107.7	102

Notes: 1 m = 3.3 ft.
Barrier height = 0.89 m, speed = 92 km/h, and angle = 17.5°. Cargo weight and initial location correspond to measured values from actual SwRI vehicle that rolled over during full-scale test.

[a]Locations in vehicle fixed reference frame (x, y, z) with origin at barrier-vehicle contact point (Figure 1).

Table 3. Effect of barrier height on school-bus collision behavior.

					Cargo Position (m)						Post-Secondary-Impact Roll Rate	
	Barrier Height	Vehicle Center of Gravity[a] (m)			Original			Displaced			Positive Toward Barrier (°/s)	Percentage of Critical Rate
Case	(m)	x_1	y_1	z_1	x_2	y_2	z_2	x_2'	y_2'	z_2'		
16	0.91	-5.39	-1.22	-0.25	-6.53	-1.27	-0.56	-6.56	0	-1.78	106.4	101
17	0.94	-5.39	-1.22	-0.23	-6.53	-1.27	-0.53	-6.53	0	-1.75	105.4	100
18	0.97	-5.39	-1.22	-0.20	-6.53	-1.27	-0.51	-6.53	0	-1.73	103.9	99

Notes: 1 m = 3.3 ft.
Speed = 92 km/h and angle = 17.5°.

[a]Locations in vehicle fixed reference frame (x, y, z) with origin at barrier-vehicle contact point (Figure 1).

are compared with those from the case 1 simulation (Table 1), which excluded cargo displacement for the 0.89-m (35-in) barrier. Further, proper delineation of the cargo center of gravity (cases 13, 14, and 15) in the computer program in comparison with the assumption that it corresponded with vehicle center of gravity (cases 10, 11, and 12) also demonstrated a greater rollover potential.

A final series of simulations was performed to determine the barrier height that would have resulted in a safe redirecting of the school bus (see Table 3). For these simulations, an assumed cargo displacement (Figure 4), defined in case 15 (Table 2), was used. As the data show, even with the barrier raised to a 0.97-m (38-in) height, the resultant roll angular velocity was extremely high (99 percent of the critical roll rate). Note that this series assumed an extreme lateral and vertical cargo displacement. However, these displacement extremes cannot be overly conservative because of the many vehicle and barrier variables involved in an actual crash that are not addressed in this simple program (e.g., vehicle and barrier deformation).

CONCLUSIONS

The problem of cargo displacement is integral to studies of the postimpact behavior of heavy vehicles in collision with barrier systems. This investigation substantiates the relationship. Moreover, the modified rollover vaulting algorithm (RVA 2) is an efficient tool with which to consider this complex phenomenon. Although the sample cases in this study were limited to those involving a school bus, RVA 2 can be used to simulate a wide range of single-unit vehicles where a potential cargo shift could contribute to hazardous vehicle behavior.

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REFERENCE

1. J.J. Labra, J. Rudd, and J. Ravenscroft. Roll-over-Vaulting Algorithm for Simulating Vehicle-Barrier Collision Behavior. TRB, Transportation Research Record 566, 1976, pp. 1-12.

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The Rural Mailbox: A Little-Known Roadside Hazard

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The results of seven full-scale crash tests conducted at the Texas Transportation Institute to evaluate the impact behavior of rural mailbox installations are reported. Three of the seven tests—two of single-box installations and one of a four-box installation—involved commonly used wood-post supports. Two tests of single-box installations involved promising new support concepts that use standard steel pipe with a breakaway mechanism. The final two tests involved a steel-pipe, multiple-box support in the shape of an inverted U. The results showed that installations with multiple boxes mounted on boards pose a serious hazard to motorists because the board can easily penetrate the windshield. The inverted-U design eliminated the penetration problem, but the change in vehicle momentum on impact exceeded the recommended limit. The results also showed that, for a single-box installation, a pipe post performs better than a wood post. Careful attention must be given to the box-to-post attachment to prevent separation during impact and thus minimize the potential for windshield penetration by the mailbox.

Little attention has been given to rural mailbox structures as potential hazards to motorists. Although the incidence of vehicle collisions with mailboxes may be small in comparison with collisions with more formidable hazards, mailbox accidents are not statistically insignificant. Table 1 gives a summary of 1972 data from four states on road accidents involving mailboxes (1). By using available accident data, the Federal Highway Administration (FHWA) has estimated that approximately 200 or more fatalities occur each year as a result of mailbox accidents.

The U.S. Postal Service issues design specifications for the rural mailbox itself and its vertical position (2), but it has no specifications for mailbox supports. In 1969, the American Association of State Highway Officials (AASHO) published guidelines for erecting mailboxes on highways, including suggested structural supports (3). Some of these recommended supports, however, were found to be undesirable in the testing reported in this paper. A cursory review of several state and county agencies reveals an almost total absence of any standards for mailbox supports. Only one state is known to have such standards.

Figure 1 shows some of the "ingenious" devices used to support mailboxes. These include steel tractor wheels, old-time stoves, water pumps, plowshares, milk cans filled with concrete, massive I-beams, and pipes. Such supports may be artistic to some, but most are serious roadside hazards.

Mailboxes are hazardous primarily because of the mounting height of the box. Most boxes are mounted approximately 42 in (106.7 cm) above ground to make it easier for the mail carrier to place mail in the box. As Figure 2 shows, this height places the box in direct line with the windshield of many vehicles. The support systems shown in Figure 2 were used for illustrative purposes only and are not considered crashworthy systems. The base of each of the three different-sized boxes is approximately 42 in above the ground.

Mounting several boxes on a wood board compounds the problem, since the board can spear through the windshield. Field installations of multiple boxes are shown in Figure 3. Figure 4 shows what may be a record for the number of boxes mounted on one continuous support (more than 200).

To gain insight into the hazard of mailbox installations, FHWA and the Texas State Department of Highways and Public Transportation (TSDHPT) elected to conduct limited full-scale crash-test