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Abstract:
This paper is concerned with the testing of a new portable energy-absorbing system to be attached to the rear of a highway service vehicle. The research objective was to design a system to provide protection for both the motoring public and the service personnel engaged in maintenance operations on our highways. Its implementation during highway line-striping operations, which are conducted on almost a daily basis, would be of particular value. The energy-absorbing components of the system are four steel pipes connected in a series and cantilevered from the rear of the service vehicle. Full-scale crash tests were conducted to evaluate the performance of the system with respect to (a) structural adequacy, (b) impact severity, and (c) vehicle trajectory. The results of this testing program demonstrate that this energy-absorbing system provides protection during a collision for both the errant motorist and the state personnel working in the service vehicle. The unit is relatively light, inexpensive to construct and repair, and is compactly designed for use on curved and hilly roads. (Author)

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Crash Testing of A Portable Energy-Absorbing System for Highway Service Vehicles

JOHN F. CARNEY III

This paper is concerned with the testing of a new portable energy-absorbing system to be attached to the rear of a highway service vehicle. The research objective was to design a system to provide protection for both the motoring public and the service personnel engaged in maintenance operations on our highways. Its implementation during highway line-striping operations, which are conducted on almost a daily basis, would be of particular value. The energy-absorbing components of the system are four steel pipes connected in a series and cantilevered from the rear of the service vehicle. Full-scale crash tests were conducted to evaluate the performance of the system with respect to (a) structural adequacy, (b) impact severity, and (c) vehicle trajectory. The results of this testing program demonstrate that this energy-absorbing system provides protection during a collision for both the errant motorist and the state personnel working in the service vehicle. The unit is relatively light, inexpensive to construct and repair, and is compactly designed for use on curved and hilly roads.

In many highway-maintenance operations, personnel and equipment are inadequately protected from collision by an errant vehicle. To provide this needed protection, several portable energy-absorbing systems have been designed. One such unit employs hi-dro cell components (1,2) attached to the rear of a follower truck in maintenance operations. Another system employs modular crash cushion elements (3), which are 208-2 L (55-gal) drums. This system has been used in the states of Washington and Texas and consists of a trailer that carries 30 crushable barrels (10 rows of 3 barrels).

A modified version of this modular crash cushion has been developed by the highway wayside equipment research office and the equipment office of the Ontario Ministry of Transportation and Communications (4). A third system, which employs crushable Hi-Dri cartridges, has also been designed and manufactured (5).

The hi-dro cell energy-absorbing system and the modular crash cushion system are a study in contrasts. They both dissipate energy on impact, but the portable hi-dro cell unit now being used is approximately 0.91-m (3-ft) long and the modular crash cushion unit is 5.94 m (19.5 ft) in length.

The hi-dro cell system consists of 5 rows of 13 polyvinyl chloride plastic cells enveloped in a corset-like membrane. The entire unit rests on a metal platform that is attached to the rear of the truck. Each cell contains approximately 13.25 L (3.5 gal) of a water-calcium chloride solution. The portable modular crash cushion system is composed of 30 steel drums (10 rows with 3 barrels/row), constructed of 20-gage steel, that rest on a trailer. The trailer is attached at five points to the truck to provide horizontal and vertical stability during impact.

The hi-dro cell unit is portable and relatively easy to install on the rear of a highway truck. Its usefulness as an energy-absorbing system is of primary concern, however, and the present design offers satisfactory protection only for relatively low speeds [less than 48 km/h (30 mph)]. For higher speeds, the present design cannot simultaneously satisfy energy absorption and minimum stopping distance (deceleration) requirements. In addition, the hi-dro cell unit is extremely heavy and has caused failure of the spring system of the truck bed to which the unit is attached.

The modular crash cushion possesses the required energy-absorption capability for speeds of up to 96.5 km/h (60 mph). Furthermore, the 5.94-m length of the barrel system, coupled with the energy-absorbing characteristics of the individual barrels, results in acceptable deceleration levels for impacts of even 96.5 km/h. The modular crash cushion clearly performs its energy-absorbing function admirably. As a practical matter, however, the length of the modular crash cushion inhibits its effective use on winding, hilly roadway networks that exist in many states of the United States.

In addition, day to day use problems have developed with the system. Tires wear much faster than expected when compared with other trailers. This problem is caused by the rigid connection required for stability between the trailer and the towing vehicle. Major difficulties associated with weld fatigue have developed. The Canadian version of the modular crash cushion has experienced similar difficulties. It has been deemed not suitable for permanent rough driving, as in striping operations, and is not recommended for widespread use.

The Hi-Dri energy-absorbing system employs lightweight concrete cylinders bonded to plywood retainer panels and placed inside a plywood box as the energy-absorbing components. The unit functions reasonably well under impact loading. The system is expensive, however, and the condition and position of the concrete cylinders should be checked regularly to ensure proper positioning in the device. This visual inspection is hampered because the energy-absorbing concrete cylinders are enclosed in a fiberglass-crated shell.

An energy-absorbing system composed of sections of steel pipes is described in this paper. The pipes are designed to incorporate the good features of the systems mentioned above, but with several advantages:

1. The pipe system is economical to build and repair,
2. The pipes can be reused after minor impacts by merely jacking them back to their original configuration,
3. The guide system and associated support devices needed in the pipe system are minimal, and
4. The system is compact and designed for use on curved and hilly roads.

BASIC PROBLEM

The basic problem involves the collision of two bodies: a passenger car traveling at a high rate of speed and a highway service vehicle moving at, say, 16.1 km/h (10 mph). Given the values of the velocity vectors of the car and truck before impact, the appropriate equations of dynamics may be applied to determine the velocities of the two vehicles after the collision and the amount of energy dissipated during impact. In this development, any rotations about the mass centers of the vehicles will be neglected.

The equations of dynamics to be employed include the principle of the conservation of linear momentum and the principle of impulse and momentum. In addition, the definition of the coefficient of restitution and the concept of kinetic energy must be employed. The application of these concepts yields the amount of energy that is to be absorbed, which depends on the following parameters:

1. Weight of the automobile,
2. Weight of the service vehicle,
3. Weight of the energy-absorbing unit,
4. Velocity of the automobile just before impact,
5. Velocity of the service vehicle just before impact, and
6. Angle of impact.

Following recommended guidelines (6), the weight of a heavy automobile was taken as 20 kN (4500 lb). The service vehicle to which the energy-absorbing unit was to be attached weighs 62.3 kN (14 000 lb) and the weight of the energy-absorbing unit was estimated at 8.9 kN (2000 lb). The velocity of the automobile just before impact was set at 88.5 km/h (55 mph) and that of the service vehicle prior to impact was taken as 16.1 km/h (10 mph) in the same direction as the car. The angle of impact was assumed to be zero degrees. For this set of data, the amount of energy to be absorbed by the portable energy-absorbing system can be calculated to be 319 107 J (235 330 ft•lb).

Energy-Absorption Characteristics of Thick-Walled Rings

Research into the feasibility of employing thick-walled rings as energy-absorbing units when loaded to complete collapse in the plane of the ring has been conducted by Perrone (7). This excellent piece of work involves both experimental and analytical studies that relate the dissipated energy in the ring to its geometry and material characteristics.

Rings that have 0.46-m (1.5-ft) diameters and 12.7-mm (0.5-in) thicknesses made of A53A, A53B, and X52 steel were tested. Uniaxial tensile specimen coupons of these steels exhibited the stress-strain characteristics depicted in Figure 1 (7). Figure 1 shows that the constitutive properties of the three steels are almost identical. Next, load-deformation tests were conducted on the three rings; these results are shown in Figure 2 (7).

Collapsing Mode

The collapsing mode of the individual pipes is as-

Figure 1. Stress-strain curves for A53A, A53B, and X52 steels.

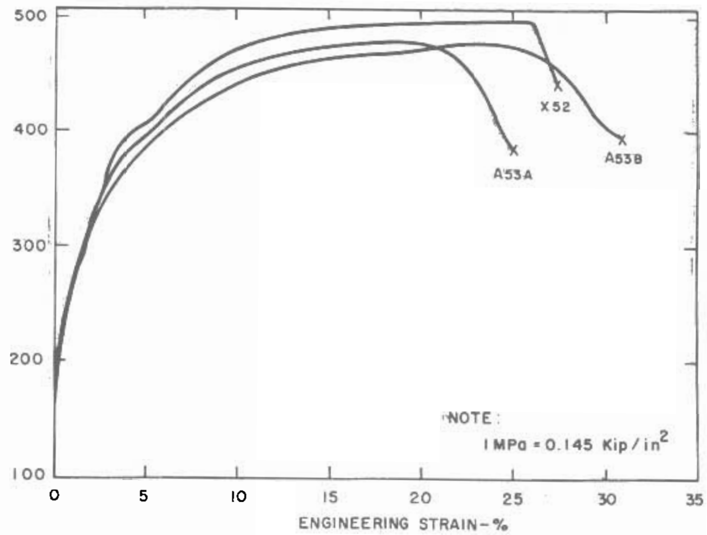
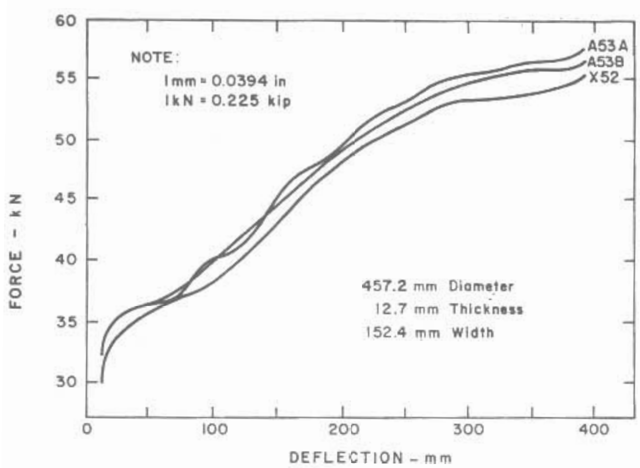


Figure 2. Force-deflection curves for three steel rings.



sociated with the formation of four plastic hinges 90° removed from one another. If we apply the theorem of virtual work and equate the internal and external work done, then

$$2 P_c (R\alpha/2) = 4 M_o \alpha \tag{1}$$

where

P_c = small deflection static collapse load,
R = radius of ring,
α = virtual angle change, and
M_o = yield moment.

It follows that the collapse load is

$$P_c = 4 M_o/R \tag{2}$$

But the yield moment at plastic collapse may be written as

$$M_o = \sigma_o Wt^2/4 \tag{3}$$

where

σ_o = static yield stress,
W = depth of ring, and
t = thickness of ring.

which leads to

$$P_c = \sigma_o Wt^2/R \tag{4}$$

Based on the uniaxial data shown in Figure 1, Perrone suggests a value of static yield stress (σ_o) of 268.9 MPa (39 kips/in²). Note that the collapsing force increases to approximately 2 P_c as the deformation of the ring increases, the energy absorbed in the ring can be closely approximated by the expression

$$\text{Energy} = 1.14 (1.5 P_c)(2 R) = 3.42 \sigma_o Wt^2 \tag{5}$$

Figures 1 and 2 and, therefore, Equation 5 are valid only under static loading conditions. Structural steel is a rate-sensitive material, however, and its properties can change by as much as 100 percent, depending on the strain rates during the deformation process. Much experimental and analytical research has been conducted in this area (8-13). For the range of strains and strain rates to be encountered in this application, Perrone (7) suggests an overall rate sensitivity factor of 1.6. In Equation 6, therefore, if the σ_c term is replaced by 1.6 σ_c, the equivalent dynamic energy absorbed can be written as

$$\text{Dynamic energy absorbed} = 5.47 \sigma_o Wt^2 \tag{6}$$

It has been shown earlier that amount of energy to be absorbed in the heavy automobile collision is 319 107 J (235 330 ft•lb). The energy-absorbing system must absorb this energy in such a controlled way as to satisfy the Federal Highway Administration's (FHWA) guidelines (6), which limit the maximum permissible average vehicle deceleration to 12 g.

It is possible to calculate the minimum required length of the energy-absorbing unit needed to slow a speeding vehicle, as a function of velocity, in order not to exceed 12 g average deceleration. From dynamics, one can write

$$V_c^2 = V_o^2 + 2as \tag{7}$$

where

V_c = automobile speed before impact,
V_o = automobile speed when automobile and truck move as a unit,
a = average vehicle deceleration, and
s = required length of energy-absorbing unit.

Figure 3. Energy-absorbing pipes.

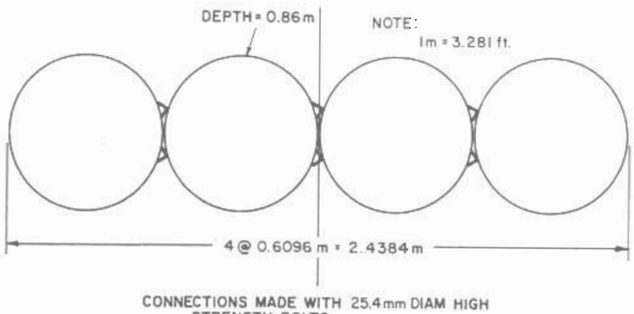
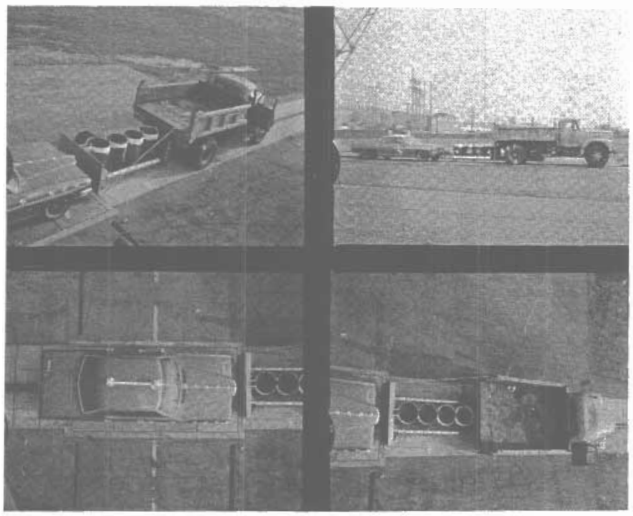


Figure 4. Portable energy-absorbing system.



Suppose the pre-impact velocity of the service vehicle is 16.1 km/h (10 mph). It follows from Equation 7 and the principles of dynamics that, for the case when the automobile impact speed is 88.5 km/h (55 mph), the minimum length of the energy-absorption system is 2.23 m (7.31 ft).

DESIGN AND FABRICATION OF PORTABLE ENERGY-ABSORBING SYSTEM

The system must absorb 319 107 J (253 330 ft•lb) of energy and possess a collapsing stroke of 2.23 m (7.31 ft). The energy-absorption capacity of one pipe is given by Equation 6. It was decided to employ as the energy-absorbing components, four 2-ft diameter pipes connected in a series, as shown in Figure 3.

Because of vertical stability considerations, the depth of the pipe system was set at 0.86 m (34 in). Then a polymodular design was carried out. In the polymodular design, the wall thicknesses of the two pipes nearest the rear of the service vehicle were taken as 9.525 mm (3/8 in). The third pipe in the series was given a thickness of 6.756 mm (0.266 in). The fourth pipe, the one nearest the impact point, has a thickness of 6.756 mm (0.266 in) and 0.508-m (1.67-ft) long vertical slits 180° apart in its sides. With this setup, the pipe system exhibits increasing stiffness as the collapse length increases. If we assume a 50 percent reduction in energy-absorption capacity in the last pipe due to the existence of the slits, it can be determined from Equation 6 that this system can, when fully collapsed, just absorb the 319 107 J (235 330 ft•lb) of energy to be dissipated.

The system has been designed to possess the following two characteristics:

1. It is capable of absorbing most of the energy dissipated in a high-speed collision between an automobile and the highway service vehicle and
2. It absorbs this energy in such a way that the accelerations and acceleration rates to which the automobile and service vehicle are subjected are within the guidelines specified by FHWA.

The energy-absorbing system involves three components:

1. Service vehicle guidance frame,
2. Energy-absorbing pipes, and
3. Impacting plate assembly.

A photograph of the system mounted on the service vehicle is shown in Figure 4. The impacting plate assembly shown in Figure 4 is constructed of 6061-T6 aluminum. The remaining components of the energy-absorbing system are made of A-36 steel. Note that the steel aluminum guide members in the impacting plate assembly slide inside the steel structural tubing on collapse of the system.

Full-Scale Crash Testing Program

The crash testing phase of the research was carried out under subcontracts by Calspan Corporation of Buffalo, New York, and the Texas Transportation Institute. Full-scale crash tests were conducted to evaluate the performance of the energy-absorbing system under different impact conditions.

Test Conditions

The first four tests were carried out by Calspan Corporation.

Test vehicle 1 was a 1971 Ford Maverick that weighed 10.05 kN (2260 lb) and impacted the 62.27-kN (14 000-lb) service truck equipped with the portable energy-absorbing system. The impact velocity was 73.69 km/h (45.8 mph). The impact angle was zero degrees and impact occurred at the centerline of the truck. The average deceleration of the automobile was 9.8 g in this crash test.

Test vehicle 2 was a 1970 Pontiac that weighed 19.93 kN (4480 lb). The impact velocity was 74.90 km/h (46.55 mph), the impact angle was zero degrees, and impact occurred at the centerline of the truck. In this test, the average deceleration of the automobile was 8.5 g.

Test vehicle 3 was a 1973 Plymouth that weighed 19.93 kn (4480 lb). The impact velocity was 73.18 km/h (45.48 mph). The impact angle was zero degrees, and impact occurred at a 0.762-m (2.5-ft) offset from the centerline of the truck. The average deceleration was 7.7 g.

Test vehicle 4 was a 1973 Plymouth that weighed 19.88 kN (4470 lb). The impact velocity was 73.66 km/h (45.78 mph). The impact angle was 10°, impact occurred at a 0.762-m (2.5-ft) offset from the centerline of the truck, and the average deceleration was 7.8 g.

During the testing program, the four automobiles and the service truck were instrumented with accelerometer packages. These test reports demonstrate the effectiveness of the energy-absorbing system. The four automobiles sustained, in view of their impact velocities, minimal damage, and the

Figure 5. Results of crash test.

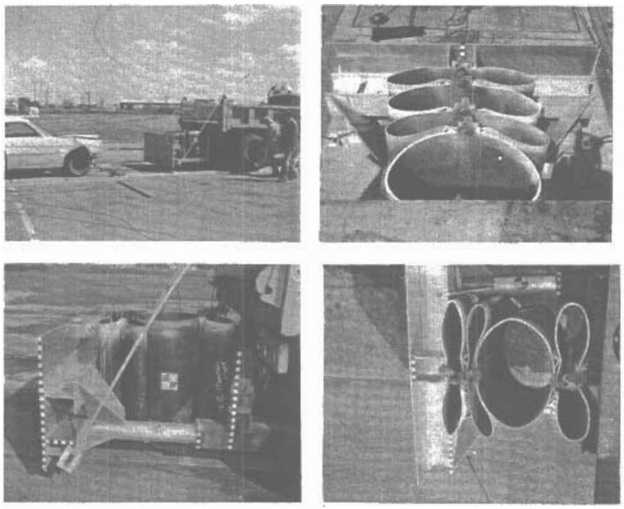
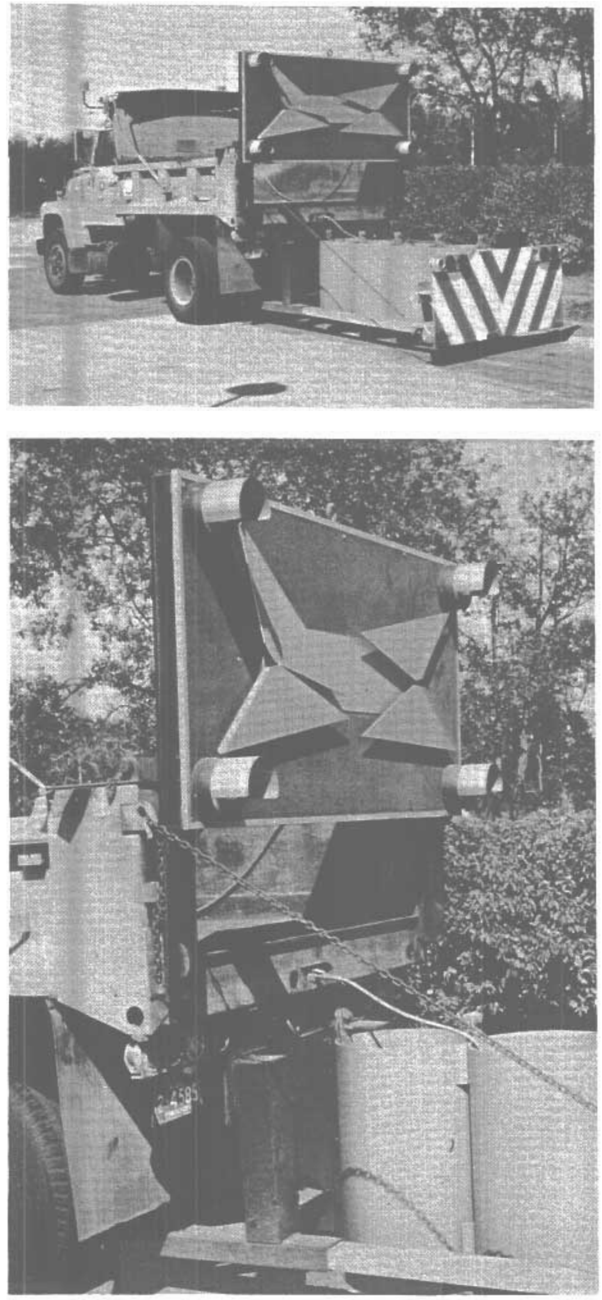


Figure 6. Connecticut portable energy-absorbing system.



service vehicle was undamaged by the four crashes. The same energy-absorbing system was employed for all four tests; the four collapsing pipes were the only system component to be replaced after each crash. Some of the crash test results are shown in Figure 5.

The deceleration levels in the three heavy car crash tests were well within the guidelines set forth (6). In the 10.1-kN (2260-lb) car crash test, however, there was an initial 80 g acceleration "spike" of approximately 10 ms duration, after which the decelerations drop to and remain at acceptable levels. This lightweight vehicle spike was caused by the existence of the 1.9-kN (430-lb) aluminum impacting plate assembly that must be moved to permit the collapse of the energy-absorbing system.

This aluminum assembly was redesigned and its weight reduced to 1.2 kN (278 lb). The light car crash test was then repeated at the Texas Transportation Institute. The acceleration spike did not occur in this test. The current design, therefore, employs the new aluminum impacting plate assembly. Final design details of the system are presented elsewhere (14). Figure 6 shows one of the eight units used by the Connecticut Department of Transportation in its daily maintenance operations.

The performance of the system has been demonstrated. The implementation of this system would provide protection for both the motoring public and the service personnel engaged in maintenance operations on our highways. It would also offer effective protection for the equipment used in these maintenance and repair projects. Of particular value would be its implementation during highway line striping operations, which are conducted on almost a daily basis. In addition, the energy-absorbing system would provide immediate temporary protection during short-term repair or clean up operations (i.e., the repairing of a Fitch sand-filled barrel system).

The energy-absorbing system possesses the following favorable characteristics.

1. It absorbs most of the energy dissipated in a high-speed collision between an automobile and the highway service vehicle, and it absorbs this energy in such a way that the accelerations and acceleration rates to which the automobile and service vehicle are subjected are within the guidelines specified by FHWA.

2. It is inexpensive to build; the total assembly can be constructed at an approximate cost of $2000. This figure compares favorably with the cost of existing competitive units.

3. It is inexpensive to repair; under most crash conditions, all that is required is to insert new 2-ft diameter pipes into the system. These pipes are bolted together and cost about $100 each. The aluminum impacting plate and the steel frame under the dump truck body will not usually require repairs. In the case of a collision at low speed, the steel pipes can be jacked back to their original shape and reused.

4. It can be attached to or removed from the service vehicle in minutes.

5. It is compact and designed for use on curved and hilly roads.

6. There is no tendency for the impacting automobile to nosedive under the energy-absorbing unit or catapult over said unit.

7. In the event of an eccentric impact, the intrusion of the impacting automobile into the adjacent traffic lane is minimal.

8. The 62.27-kN (14 000-lb) service vehicle can be expected to suffer no damage during the crash, and adjacent lane intrusion by the truck is not a problem. The same service vehicle was used for all crash tests and suffered no damage.

ACKNOWLEDGMENT

This work was accomplished in cooperation with the Connecticut Department of Transportation and FHWA. The contents of this paper reflect my views, and I am responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the state or FHWA. This paper does not constitute a standard, specification, or regulation.

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Abridgment