# Vehicle guard rails for roads and bridges

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# Vehicle Guard Rails for Roads and Bridges

*Glissières de sécurité pour routes et ponts*

*Leitplanken für Straßen und Brücken*

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## Introduction

Although there have been many full-scale tests of vehicles striking specific designs of guard rails for use on roads, and sometimes of bridge-parapet railings, there appears to be a lack of information regarding the forces involved in such collisions.

In this paper the action of a vehicle striking a guard rail at glancing incidence is examined from first principles in an attempt to determine both the order of the forces which the barrier must withstand, and the effect of its physical characteristics on the subsequent behaviour of the vehicle. The simple theoretical treatment, which applies equally to road barriers and bridge-parapet railings, is supplemented by the results of controlled impacts.

## The Approach Angle

One of the initial functions of guard rails was to prevent vehicles leaving the road at sharp bends. Today they are being used increasingly on high-speed roads with gentle curves to prevent vehicles crossing narrow central reservations. It is of interest to establish the likely range of impact angles in the two cases. In a typical accident at a sharp bend the impact angle is unlikely to be greater than that obtaining should the vehicle continue in a straight path (Fig. 1a). On a high-speed road impact occurs when the vehicle veers across the road (Fig. 1b). In both cases the impact angle $\theta$ is given by the expression

$$\theta = \cos\frac{(R-b)}{R}, \quad (1)$$

where $R$ = radius of curvature of road (Fig. 1a) or of the path of the vehicle (Fig. 1b) and $b$ = distance across the road at which the vehicle starts to deviate from the direction of the road.

Fig. 2 shows the relationship between $\theta$ and $R$ for values of $b = 10$, 20 and 30 ft. Sharp bends are usually found on two-lane single carriageway roads, so

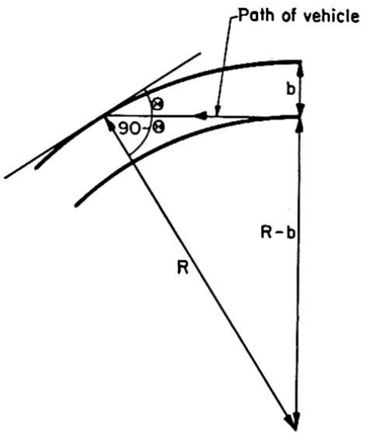


Fig. 1a. Vehicle continuing in straight path at a sharp road bend.

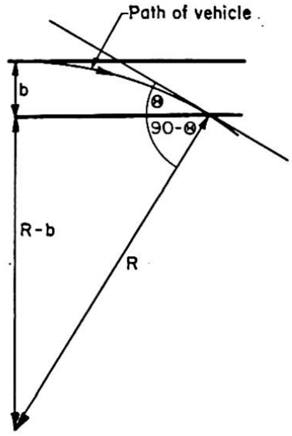


Fig. 1b. Vehicle swerving across a straight road.

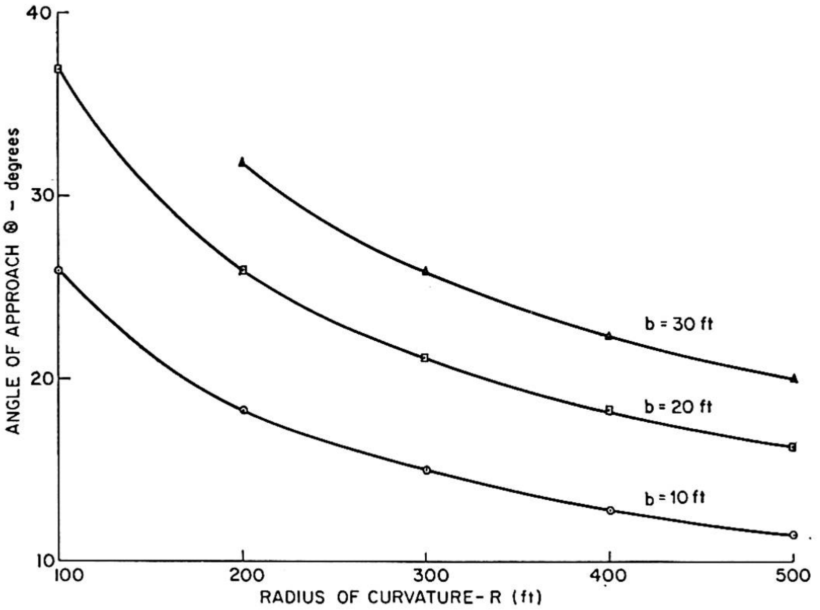


Fig. 2. Relationship between radius of curvature and angle of approach.

that for the vehicle approaching the bend the value of $b$ is likely to be about 10 ft., and the corresponding values of $\theta$ within the range 11—26 deg.

When a vehicle swerves across the road the minimum radius of curvature it can follow without overturning is related to its velocity. In Fig. 3, $G$ is the centre of gravity of a vehicle moving in a curved path, and $P$ is the centre of pressure of a guard rail. Considering first the case when there is no guard rail, and therefore no reaction at $P$, and taking moments about $G$, assuming for simplicity that the centre of gravity does not move relative to the wheels, overturning will start to occur when

$$\frac{m v^2}{R} h_1 > m g c$$

$$v^2 > \frac{g R c}{h_1}, \qquad (2)$$

where $m$ = mass of vehicle,
$v$ = velocity,
$h_1$ = height of centre of gravity,
$c$ = half the distance between the wheels,
$g$ = acceleration due to gravity = 32.2 ft./sec$^2$.

For a typical car $c/h_1 = 1.1$, hence

$$v^2 > 35.4\,R.$$

Numerical values are given in Fig. 4. Knowing the minimum possible radius of curvature for a given speed the appropriate value of $\theta$ can be obtained from Fig. 2 for a specific value of $b$. The value of $b = 30$ ft. corresponds to a vehicle swerving across a three-lane road, the worst case; at 60 mile/h the maximum possible angle of approach is 30 deg. On a two-lane road a value $b = 20$ ft. will approximate to the worst case of a car swerving across the full road width;

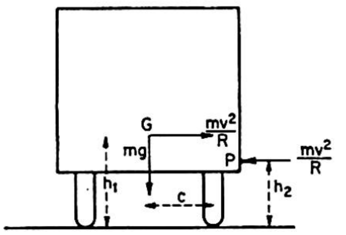


Fig. 3. Principal forces acting on a vehicle moving in a curved path.

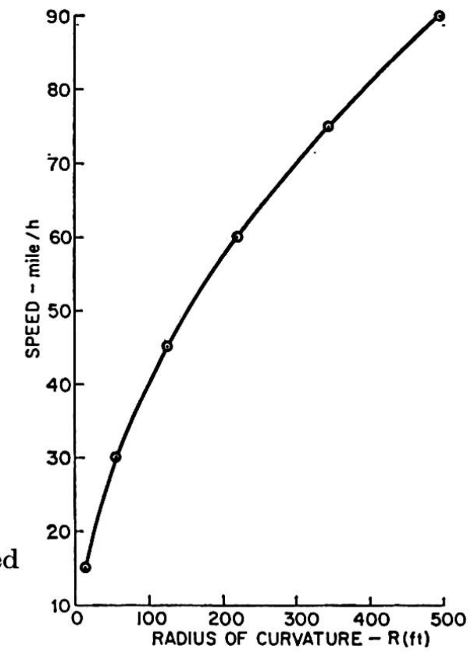


Fig. 4. Relationship between overturning speed and radius of curvature for private cars.

at 60 mile/h the maximum possible angle of approach is 25 deg. Thus it appears that the possible approach angles when a vehicle swerves across the road are of the same order as those at sharp bends, and that values as high as 30 deg. are possible. However, on two-lane carriageways, which will include most bridges and elevated roads, an approach angle of 20 deg. is probably more representative of the severe impacts which occur in practice.

## The Force of Impact

The force to which a barrier is subjected by a glancing blow from a vehicle can be approximately evaluated by considering the distance in which the component of the approach velocity perpendicular to the barrier is reduced to zero. Thus in Fig. 5 $RR$ is a rigid barrier and $G$ the position of the centre of gravity of the vehicle. Then if $v_p$ is the velocity component perpendicular to the barrier, and $l$ the distance of the centre of gravity from the front of the vehicle, we have

$$\text{transverse deceleration of vehicle,} \quad a = \frac{v_p^2}{2s},$$

where $s = l \sin\theta$.

If the barrier is flexible the distance in which the perpendicular velocity is destroyed is $(s+d)$ where $d$ is the maximum instantaneous deflection of the barrier, and

$$a = \frac{v_p^2}{2(s+d)}. \tag{3}$$

An approach of 60 mile/h at 20 deg., i.e. velocity perpendicular to the barrier of about 20 mile/h, is probably representative of most severe impacts.

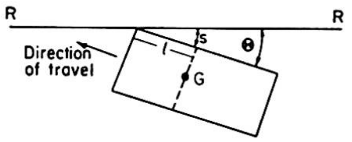


Fig. 5. Glancing impact of vehicle with rigid barrier.

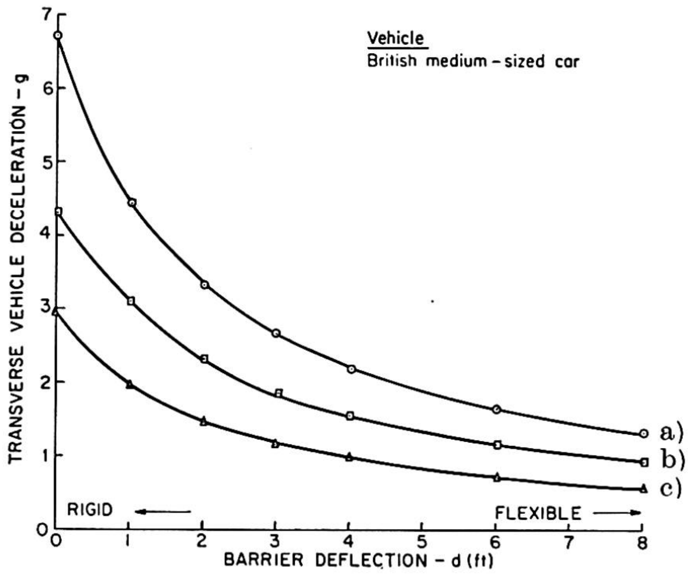


Fig. 6. Relationship of transverse vehicle deceleration and barrier deflection at various speed for an approach angle of 20 deg.

Speed a) 60 mile/h
b) 50 mile/h
c) 40 mile/h

At the Road Research Laboratory tests have been carried out using British medium-sized cars with a laden weight of 3000 lb., and for which the centre of gravity is 6 ft. from the front of the vehicle. Fig. 6 shows the relationship between transverse vehicle deceleration and barrier deflection for such a vehicle, at an approach angle of 20 deg. and speeds of 40—60 mile/h. For a rigid barrier the average transverse deceleration during impact at 60 mile/h is 6.7 $g$. For a barrier which deflects as much as 4 ft. the deceleration is 2.2 $g$. Metal and concrete guard rails mounted on posts deflect between these extremes, and therefore will be subject to accelerations within the limits 2.2—6.7 $g$ for impacts at 60 mile/h. Knowing the transverse acceleration the corresponding average force on the rail is obtained from force = mass $X$ acceleration.

In one test a car struck a reinforced concrete guard rail at 46 mile/h and

20 deg. The instantaneous rail deflection was 9 in. and hence the transverse vehicle deceleration was $2.8g$, and the average force on the rail 8400 lb. A corrugated metal beam struck at 50 mile/h and 18 deg. deflected $1\,{}^{1}/_{2}$ ft. Hence the transverse deceleration was $2.3g$ and the average force on the rail 6900 lb.

For a specific approach the deceleration of a heavy vehicle will be less than that of a car because of the greater distance from the front of the vehicle to its centre of gravity. If for a vehicle with a total mass 10 times that of a car, i. e. 30,000 lb., the centre of gravity is twice as far from the front end, i. e. 12 ft., the force applied to a rigid barrier will only be 5 times that of the car. Thus, at a perpendicular velocity of 20 mile/h the force on the barrier will be $5 \times 6.7 \times 3000 = 100{,}000$ lb. (about 45 tons). This is probably the order of the greatest average force to which a guard rail is likely to be subjected, since any deflection of the rail itself will reduce the force applied. It is of interest to note that RINKERT [1] conducted tests having as their objective the design of a bridge railing which would withstand the impact of a 15-ton bus at a perpendicular velocity of 31 mile/h, this being the maximum permissible speed for Stockholm's buses. The final design successfully contained such impacts, but with considerable deflections of posts and rail.

The decelerations referred to above are average values derived from the lateral displacements of the centre of gravity of the vehicle. For severe impacts against beams with lateral stiffness decelerations recorded in the test cars exhibit two short duration peaks corresponding to separate impacts from front and rear ends of the cars. Thus, in the tests already mentioned a peak value of $10g$ was recorded against the concrete guard rail, and $6.7g$ against the metal rail, i. e. about 3 times those of the average values. Recorded decelerations against flexible wire rope barriers do not show marked short duration peaks.

Barriers should probably be designed to withstand the peak forces to which they are subjected. These can be found from the forces (calculated in this paper) which must then be multiplied by a factor of about 3 for the beam type barriers. This value may have to be revised in the light of future experiments.

## The Rail Tension

A knowledge of the force applied transversely to a guard rail enables the tension in the rail to be estimated. Thus, in Fig. 7

$$T = \frac{F}{2 \sin \alpha},$$

where $\alpha$ is the angle of deflection of the rail, which can be found from the length of rail damaged and its instantaneous maximum deflection. Tension can be measured accurately in a flexible barrier of the wire rope type by inserting a suitable load cell. In one test the approach of a car was at 46 mile/h and 20 deg. The deflection of the ropes was 4 ft. and the total length of the damaged section 80 ft.; hence $\tan\alpha = 0.1$ and $\alpha = 6$ deg. The acceleration corresponding to the 4-ft. deflection was $1.26\,g$, hence $F = 3780$ lb. and the tension $T = \frac{3780}{2\sin 6} = 18{,}900$ lb. The tension measured 8 ft. from the impact point was 20,000 lb. (10,000 lb. in each of two ropes at the same height).

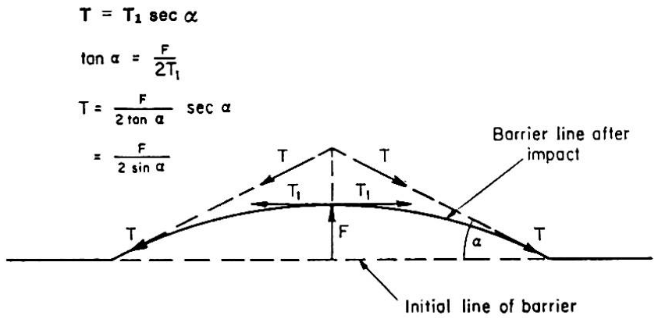


Fig. 7. Approximate relationship between the tension in a guard rail and the applied lateral force.

The estimated tension in the concrete guard rail for the test run already mentioned (46 mile/h at 20 deg.) is

$$T = \frac{8400}{2\sin 6.5} = 37000\,\text{lb.}$$

Similarly the estimated tension in the double-sided corrugated-steel guard rail for an impact at 50 mile/h and 18 deg. is

$$T = \frac{6900}{2\sin 9.5} = 23000\,\text{lb.}$$

Actual rail tensions will be greater than those estimated in this way, by the amount of the force associated with the longitudinal vehicle deceleration. This additional effect is unlikely to be important however if the impacting vehicle is redirected smoothly by sliding along an appreciable length of the rail, this being the desired vehicle reaction.

## The Vehicle Reaction

The behaviour of the vehicle after impact with the barrier will now be considered in the simplest terms, the treatment being no more than a first approximation. In Fig. 3, $h_2$ is the effective height of the guard rail. Taking moments about the centre of gravity of the vehicle, overturning will start to occur if

$$\frac{m v^2}{R}(h_1 - h_2) > m g c, \qquad v^2 > \frac{g R c}{h_1 - h_2}, \tag{4}$$

where $v$ is the velocity along the line of approach. It will be seen that if the effective height of the guard rail is equal to that of the centre of gravity of the vehicle, the latter will not overturn. If there is a difference in height between the centre of gravity of the vehicle and the effective height of the guard rail, the critical velocity for overturning will increase as the square root of the radius of curvature of the vehicle path. Eq. (4) can be rewritten as

$$a > \frac{g\,c}{h_1 - h_2}.$$

For the concrete guard rail mentioned earlier $h_2 \cong 1$ ft., and therefore for the British medium-sized car the critical transverse deceleration is about $2.2\,g$. In an approach at 31 mile/h and 20 deg. the rail deflected 3.3. in., so that the vehicle deceleration was $1.5\,g$. The wheels remote from the barrier were lifted off the ground during impact, but the vehicle did not overturn. In the approach at 46 mile/h and 20 deg. already referred to, the transverse deceleration was $2.8\,g$, and the vehicle did in fact overturn towards the rail after being reflected from it (Fig. 8). These results suggest that in so far as the behaviour of the vehicle is concerned, the average deceleration values rather than the short duration peaks are appropriate. The effective height of the corrugated metal rail was about 2 ft., and it successfully reflected a car approaching at 50 mile/h and 18 deg. with no rolling motion towards the rail (Fig. 9).

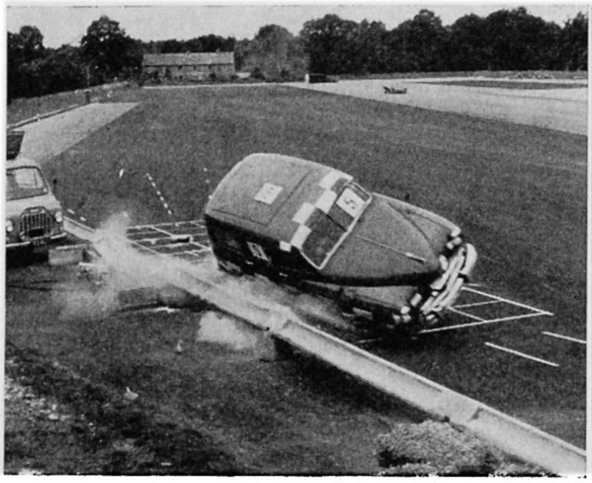

Fig. 8. Impact with D.A.V. concrete guard rail at 46 mile/h and 20 deg.

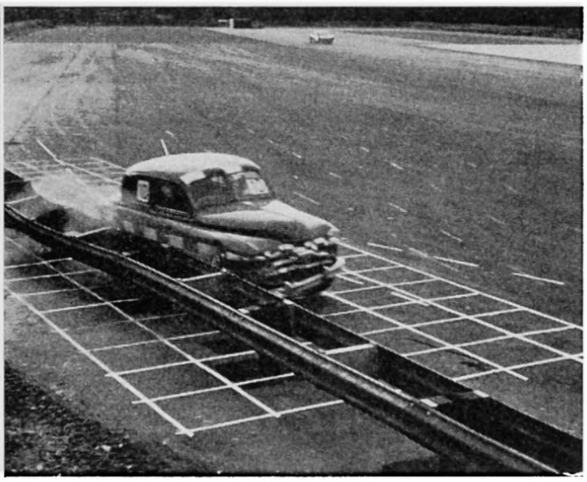

Fig. 9. Impact with blocked-out metal guard rail at 50 mile/h and 18 deg.

Thus, it appears that a continuous beam or rope, with sufficient strength in tension, mounted at 2 ft. above ground, should successfully redirect private cars without overturning them. The centre of gravity of heavy commercial vehicles may vary between the approximate limits of 4—8 ft. however, so that the rail at 2 ft. could still cause such a vehicle to overturn. This is a fundamental difficulty concerning guard rails for roads; it is alleviated to some extent by the fact that for a specific approach the heavy vehicle will deflect the rail more than the car, with a consequent reduction in the transverse deceleration. The economics of bridges and elevated roads are such that it is feasible to provide two horizontal rails, one at about 2 ft. for cars and another at 4—5 ft. for heavy vehicles. Account should be taken of the increased bending moment of the top rail, however, when specifying the posts and their attachments to the bridge deck. The fundamental difficulty in this instance is the small space available for deflection of the beams.

The effect of a barrier on vehicle behaviour should be the same throughout its length; the extreme designs, viz. the very rigid and the very flexible, meet this requirement. A continuous rail mounted on very strong posts however will deflect less for impact at a post than midway between posts, and if the strengths of posts and rail are badly mismatched the vehicle may be trapped in the pocket formed between two posts.

## Road Barriers

The two basic designs of road barrier are the continuous beam with lateral stiffness, and the flexible wire rope type. Both are intended to redirect an offending vehicle smoothly and with transverse decelerations which are tolerable to the occupants. Vehicle impact with the posts is implicit in the design of the wire rope barrier, the posts being too weak to stop the vehicle. With the beam type guard rail however violent longitudinal deceleration will occur if the contacting wheel or lower parts of the vehicle are forced under the rail to strike a post. This eventuality becomes less likely if the rail is mounted clear of the posts by means of rigid blocking-out pieces; another benefit is that the rail tends to retain its initial height when the posts are forced back. In the arrangement successfully tested at the Laboratory the 12-in. wide metal beams were blocked out 9 in. from the posts, at a height of 21 in. to the rail centre. Soil-mounted timber posts are satisfactory in that they rotate about a point below rather than at ground level, thus allowing a larger lateral deflection of the rail before impact with the posts occurs.

## Bridge Barriers

Where beam-type guard rails are used on bridges lateral movement at the base of the posts is not usual, deflection being obtained solely by the bending of the posts, which are often I-section beams welded to fixed base plates. To minimize the risk of impacts with the posts, blocking-out of the beam would appear to be even more essential in this case than where the posts can be mounted in soil.

In so far as the wire rope barrier uses posts with rigid base fixings it would be equally as effective on a bridge, always provided that it could be mounted sufficiently far from the edge. The allowable deflection of the barrier might be reduced by using ropes with a diameter larger than the normal $^3/_4$ in., and perhaps applying an appreciable initial tension. Fig. 6 shows that a reduction in deflection from 8 ft. to 3 ft. only doubles the lateral deceleration of a car.

When vehicle barriers of any type are erected at the edge of the carriageway on a bridge it will often be necessary to provide a pedestrian footwalk and a parapet railing. This outer railing should be strong enough to provide a second line of defence to an out-of-control vehicle.

A common form of edge carriageway barrier is some form of kerb.

Fig. 10. Damage to bridge parapet railing after impact from sports car.

Frequently a bridge railing must act both as a vehicle and a pedestrian barrier. Fig. 10 shows such a barrier after impact from a sports car. The posts and the continuous top rail provide the strength of the structure, the rest functioning merely as an unclimbable infill. Failure of the infill allowed the car to strike a post, with consequent serious injuries to the occupants. Thus, a continuous horizontal rail at about 2 ft. above ground, and proud of the posts, is essential to redirect cars. The fact that this will afford an easy means of climbing the railing should be the secondary consideration.

## Conclusions

Information is given relative to the order of the maximum approach angle of a vehicle striking a guard rail at specific locations on roads and bridges. Average vehicle decelerations for such impacts are derived and it appears that they are appropriate to the subsequent vehicle behaviour. It is not yet certain, however, whether average lateral decelerations or their peak values apply when estimating the forces imparted to the guard rail. For two semi-rigid guard rails tested the peak deceleration values are about 3 times those of the derived average values.

## Acknowledgement

This paper is published by permission of the Director of Road Research.

## Reference

1. A. RINKERT: "Ability of Bridge Parapets to Withstand Impact of Vehicles." Prelim. Publ. Int. Ass. Bridge and Struct. Engng. Congress, 1956, Part Ib6, 249—261.

## Summary

The dynamic behaviour of guard rails intended to resist vehicle impacts is discussed. By means of a simple theoretical model average lateral decelerations for a car incident at 60 mile/h and 20 deg. are estimated to be $6.7\,g$ for a rigid barrier, and $2.2\,g$ for a barrier which deflects 4 ft. Measured vehicle decelerations against concrete and metal guard rails show peak values about 3 times the average values. It appears likely that peak forces are appropriate for design loadings of the barrier itself, but that average deceleration values may determine whether or not the vehicle will overturn after impact.

## Résumé

On a étudié le comportement dynamique de glissières de sécurité destinées à résister aux chocs de véhicules automobiles. A l'aide d'un modèle théorique simple, on a estimé la décélération transversale moyenne d'un véhicule roulant à 96 km/h et heurtant la glissière sous un angle de 20°; cette décélération moyenne est de 6,7 g dans le cas d'une glissière rigide et de 2,2 g dans le cas d'une glissière déformable prenant une flèche de 1,2 m. Avec des glissières métalliques ou en béton, les décélérations maximum mesurées sont environ 3 fois plus grandes que les valeurs moyennes. Il apparaît légitime de calculer la glissière selon ces valeurs maximum, mais c'est des valeurs moyennes de la décélération que semble dépendre le retournement du véhicule quand il heurte la glissière.

## Zusammenfassung

Der Beitrag befaßt sich mit dem dynamischen Verhalten von Leitplanken beim Aufprall von Fahrzeugen. Mit einem einfachen theoretischen Modell wird die mittlere seitliche Verzögerung eines Fahrzeuges, das mit 60 mile/h unter 20° auf die Leitplanke auffährt, abgeschätzt. Sie beträgt 6,7 g für starre Leitplanken und 2,2 g für eine Leitplanke, die sich 4 ft. ausbiegen läßt. Verzögerungsmessungen bei Fahrzeugen, die auf Stahl- oder Betonleitplanken aufprallen, zeigen Spitzenwerte, die ca. dreimal mehr betragen als der geschätzte Mittelwert. Es ist zweckmäßig, wenn die Spitzenwerte bei der Berechnung der Leitplanken berücksichtigt werden. Der Mittelwert der Verzögerung ist dafür maßgebend, ob sich das Fahrzeug beim Aufprall überschlägt.