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Sliding and Rollover on Highways - Subtleties to Note

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ABSTRACT

While the horizontal curves have a duty to protect all types of road vehicles against sliding as well as rollover, the fact that different vehicle types lose their stability for competing criteria makes this task difficult and vital. In relation to the sliding and rollover of a vehicle undergoing centripetal acceleration, this technical note discusses a number of unclear interpretations of some statements seen in reference books and how their better understanding should be. This note has been prepared to observe such benefits as accident investigations, determination of pavement rehabilitation frequencies, and most importantly, ensuring the correct student learning.

Keywords: Static stability factor, rollover threshold, tripped rollover.

1. INTRODUCTION

Whereas sliding is adequately discussed in many highway engineering books [1-18], it is prominent that the topic of rollover (also known as overturning) has found no mention in these sources. Yet, rollover type accidents are the second most fatal accidents after head-on collisions [19]. It has been proven that a loaded truck rolls over at a speed of 25 km/h on a 20 m radius curve [20] and at only 5 km/h above the design speed on a minimum radius curve [21]. More interestingly, even if the trailer of a truck begins to roll over, the driver in the front cabin, which has a lower centre of gravity, may not be able to feel the danger [22]. Certain statements in a limited number of books containing discussions on rollover however, are sometimes misinterpreted (Section 2). These details may be overlooked in newly prepared textbooks or lecture notes and erroneous interpretations may have been repeated to date. Before commencing the discussion of the topic, the dynamics of sliding and rollover with point mass [23] simplification[†] will be summarised here.

On a level surface, the forces acting on a vehicle (Figure 1) moving in a circular motion in the plan view are its weight (mg), the centrifugal reaction (mv^2/R), and the frictional force (μmg). In order for this vehicle (with rigid wheels and body) not to slide laterally, the

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[†] With increasing number of wheels of the vehicle, the point mass simplification becomes rather cumbersome.

frictional force must be greater than the centrifugal reaction ($\mu mg > mv^2/R$). Hence, the critical speed for sliding will be

$$v = (\mu gR)^{1/2} \quad (1)$$

The critical speed for rollover on the other hand, by equating the overturning and restoring moments about point A, from $h(mv^2/R) = (e/2)mg$, will be

$$v = (egR/2h)^{1/2} \quad (2)$$

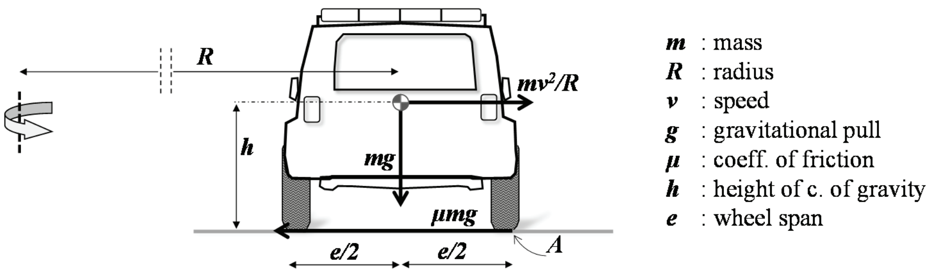

Figure 1 - Forces acting on a vehicle, rotating in the horizontal plane (lateral slope = 0)

From (1) and (2), $\mu = e/2h$ and $h = e/2\mu$ are obtained (since $\mu = v^2/gR$ from physics) and called the static stability factor [24] and the rollover threshold [25], respectively. If the vehicle moves along a horizontal curve with a superelevation of $\alpha°$, (1) and (2) become $V_s = 11.3\sqrt{\dfrac{R(\mu + \tan\alpha)}{1-\mu\tan\alpha}}$ and $V_r = 11.3\sqrt{\dfrac{R(h\tan\alpha + e/2)}{h-(e/2)\tan\alpha}}$, respectively. Here, V_s and V_r are the critical speeds in km/h for sliding and overturning. The case of $\alpha = 0°$ (without superelevation) is a special form of these two equations which produces the same outcomes as (1) and (2). The basic assumption of rigid wheels and body is common [26] but if wheel and suspension flexibilities are to be taken into account, the dynamic stability factor [27] should be used instead.

2. INTERPRETATION DETAILS AND CLARIFICATION

At certain academic platforms like thesis defence or promotion exams, such lacking or erroneous interpretations as "V_r is always greater than V_s", "if the speed of the vehicle is between V_s and V_r, it will slide, and if it is greater than V_r, the vehicle will roll over", or "if the speed of a sliding vehicle increases to V_r, it will also roll over" have sometimes been noted. In this context, when sources are referred to for the subject of rollover, the following statements appear: "… the majority of the accidents occurred at horizontal curves are due to sliding rather than overturning" [28], although no reference is cited to support this claim; "… vehicles first slide then overturn" [29]; "… on a wet pavement, a truck will roll over before it skids at design speeds of 64 to 80 km/h and below; above that speed, a truck will skid before it rolls over" [30]; "Cars rarely overturn without sliding first" [31]; "in the real world the critical speed for overturning is greater than that of sliding", "… it shows that sliding occurs at horizontal curves more easily" [32], although this holds only for vehicles with a low level of centre of gravity; "… the relative danger of lateral skidding and overturning depends on whether μ is lower or higher than $e/2h$" [33]; "a vehicle on a (horizontal) curve will overturn … about the point *m* if it exceeds a certain speed value", "… while the weight of the vehicle plays no role in its sliding or overturning, rather, *h* and *e* do have an effect" [34] , although *h* and *e* have no effect on sliding. Therefore it is very important that the issue is appropriately explained.

It should be remembered that Equation (2) was derived by taking moments about point *A* (Figure 1). As known from physics, in order to be able to take moments, the pivot must be a fixed point[‡]. In other words, since the vehicle will start to slide in a straight line tangential to the circular arc as a result of V_s, theoretically, this moment will never be taken and the overturning will never happen. In more engineering terms, the lever arm of the system will escape under the loading. As long as the lateral friction demand (v^2/gR) due to centripetal acceleration does not reach the threshold level (μ) to give rise to a slide, point *A* will act as a fixed support. Hence the vehicle will roll over only if a sufficient moment builds up as a result of the centrifugal reaction. That is to say, in order for a rollover to take place, (in basic terms) the vehicle must not be in a sliding fashion. However much the longitudinal speed of the vehicle increases, in theory, as long as μ remains constant, the (sliding) vehicle will not roll over. In this case, the question of how the rollover accidents, initiated by a slide, take place comes to mind. Possible answers are as follows:

a-As known, surface roughness is not homogenous and surface wetness varies quite often [35]. Moreover, modern cars on dry pavements can generate friction values as high as 0.9 [36]. As the coefficient of friction changes, in the direction of lateral travel, to a much higher value than that of used in design, the rollover, rather than sliding, will suddenly become critical. For instance, while a passenger car with a roof rack luggage (e = 1.6 m, h = 0.95 m, R = 100 m, V = 110 km/h, α = 2.86° (5%), μ = 0.2) is sliding, it will roll over as a result of a sudden change of μ to a value of 0.85 or higher. If the moment caused by a shock effect of a sudden slowing down is taken into account (see the numerical example below), the rollover can take place even if the coefficient of friction falls short of 0.85.

b-Similarly, road surface defects such as corrugation, potholes or roadside obstacles, may behave as hinge points and can bring lateral sliding to a stop by a great deal of deceleration. This time the speed of sliding drops to a complete zero and the momentum caused by the inertia and the already existing centrifugal reaction (mv^2/R) together transfer sliding to roll over. For example, while a car (m = 1300 kg, h = 0.7 m, e = 1.7 m, V = 100 km/h, R = 100 m, α = 2.86° (5%), μ = 0.6) is sliding with a 'sliding speed' of 4 m/s, as a result of tripping (hitting a low level fixed obstacle at right angle), with an assumption that the sliding comes to a complete stop within a quarter of a second, the car will eventually roll over (perhaps more than once), since $m\{(v^2/R)\cos\alpha + (4/0.25)\}\, h > m\{g\cos\alpha\,(e/2) + g\sin\alpha\, h + (v^2/R)\sin\alpha\,(e/2)\}$. When the values are substituted, $(7.7+16)\ 0.7 > 8.33 + 0.34 + 0.33$. In the

[‡] In case of both the pivot and the force move together in the same direction (if the replacement speed of the application point of the force is greater than that of the pivot), it is still possible to take moments. But because Equation (2) was derived, this detail had not been taken into consideration, only the case of a fixed pivot (point *A* does not shift laterally) will be dealt with in the present note.

literature this phenomenon is called a 'tripped rollover' [27]. Obviously, questioning the roadway design criteria is outside the scope of this note, but these numerical examples rather demonstrates that, at least mathematically, rollover can suddenly become critical and the shock effects may possess considerable contribution.

c-As a matter of fact, like sliding, rollover too takes place over a certain period of time. A vehicle which is in rollover state, as a result of lateral inertia, may first slide for a short period of time.

d-Although, in theory, it seems that a sliding vehicle will continue to slide until it exhausts its kinetic energy, in practice, sliding is limited by the width of the roadway. Therefore, when this width comes to an end, the vehicle will roll over as a result of either tripping, undergoing a higher μ of a soft shoulder, or suffering from an adverse ditch slope.

e-Other than these, though out of scope, a sliding vehicle will also roll over as a result of severe braking, oversteering, cross wind, hydroplane effect, bouncing, and so on.

Although propositions like "whichever of (1) or (2) is smaller, that speed is the critical speed" and "for passenger cars with no roof rack luggage (1) is always smaller than (2)" are mathematically correct, it is risky to generalise the statements above [28, 34], implying that "sliding is always more critical than overturning for passenger cars". This claim only holds for critical μ (or below) where point A cannot undertake the role of being a fixed hinge for the entirety of the sliding area.

3. CONCLUSION

For increasing values of coefficient of friction, it is a handicap for the same road to become safe against sliding, and, at the same time, less safe against rollover. In design, the friction factor against sliding is chosen low with some margin of safety (for example, according to AASHTO recommendations, on a horizontal curve the value is taken as 0.12 for 100 km/h design speed corresponding to 4%-8% of superelevation) [37, 38], assuming that some of the friction demand is compensated by superelevation. However, real friction values could easily be much higher as discussed above, making rollover potentially critical. This therefore means that whereas a road which is thought to be safe against rollover, as a matter of fact, turns out to be risky especially during dry weather due to sudden roughness changes. Because of this, very importantly, curved freeway exit ramps, where design speeds are likely to be exceeded, possesses high rollover potential. Besides, the rigid wheel/body assumption leads to less conservative results and wheel deflections and body rolls may need to be taken into consideration for safe design and good practice.

Symbols

e : lateral wheel span (m)

g : gravitational acceleration (9.81 m/s^2)

h : height of centre of gravity from road surface (m)

m : vehicle mass (kg)

R : radius of circular motion (m)

v : longitudinal speed of vehicle (m/s)

V : longitudinal speed of vehicle (km/h)

α : angle of lateral slope (superelevation)

μ : coefficient of friction between road surface and wheels

References

[1] IHT, Roads and Traffic in Urban Areas, London: HMSO, 1987.

[2] Macpherson, G., Highway and Transportation Engineering and Planning, Harlow: Longman Scientific & Technical, 1993.

[3] Lamm, R., Psarianos, B., Mailaender, T., Highway Design and Traffic Safety Engineering Handbook, New York: McGraw-Hill, 1999.

[4] Rogers, M., Highway Engineering, Oxford: Blackwell, 2003.

[5] Roess, R., Prassas, E., McShane, W., Traffic Engineering, London: Pearson Prentice Hall, 2004.

[6] Tunç, A., Yol Güvenlik ve Mühendisliği Uygulamaları, Ankara: Asil Yayın, 2004.

[7] Wright, P., Dixon, K., Highway Engineering, Wiley, 2004.

[8] KGM, Karayolu Tasarımı El Kitabı, Ankara: KGM, 2005.

[9] Fwa, T., The Handbook of Highway Engineering, Boca Raton: Taylor & Francis, 2006.

[10] Jha, M., Schonfeld, P., Jong, J., Kim, E., Intelligent Road Design, Southampton: WIT Press, 2006.

[11] Brockenbrough, R., Highway Engineering Handbook, New York: McGraw Hill, 2009.

[12] Hoel, L., Garber, N, Sadek, A., Transportation Infrastructure Engineering, Stamford: Cengage Learning, 2011.

[13] Chakroborty, P., Das, A., Principles of Transportation Engineering, New Delhi: PHI Learning, 2012.

[14] Mannering, F., Washburn, S., Principles of Highway Engineering and Traffic Analysis, Hoboken: Wiley, 2013.

[15] Robinson, R., Thagesen, B., Road Engineering for Development, London: Spon Press, 2004.

[16] Kutz, M., Handbook of Transportation Engineering, New York: McGraw-Hill, 2004.

[17] Fricker, J., Whitford, R., Fundamentals of Transportation Engineering: A Multimodal Systems Approach, New Jersey: Prentice Hall, 2004.

[18] Findley, D., Schroeder, B., Cunningham, C., Brown, T., Highway Engineering, Amsterdam: Elsevier, 2016.

[19] NHTSA, Rating System for Rollover Resistance-265, National Academy of Sciences, Washington, DC, 2002.

[20] Elvik, R., Høye, A., Vaa, T., Sørensen, M., The Handbook of Road Safety Measures, Bingley: Emerald Group Publishing, 2009.

[21] Wolhuter, K., Geometric Design of Roads Handbook, Boca Raton: Taylor & Francis, 2015.

[22] Lay, M., Handbook of Road Technology, New York: Spon Press, 2009.

[23] Günay, B., Enine İvme ve Sademe Formülleri Üzerine Bir Eleştiri, SDÜ Fen Bilimleri Enstitüsü Dergisi, cilt 15, pp. 56-59, 2011.

[24] O'Flaherty, C., Highways; Traffic Planning and Engineering, Victoria: Arnold, 1986.

[25] Gillespie, T., Fundamentals of Vehicle Dynamics, Warrendale: Society of Automative Engineers, Inc., 1992.

[26] Günay, B., Fişekçioğlu, Y., Yatay Kurp Tahkiklerinde Ball-bank Tekniğinin Kullanımı, Teknik Dergi, cilt 26, no. 3, pp. 7167-7182, 2015.

[27] Jin, Z., Li, B., Li, J., Dynamic Stability and Control of Tripped and Untripped Vehicle Rollover, Morgan & Claypool, 2019.

[28] Umar, F., Yol İnşaatı Dersleri, İstanbul: İTÜ Yayınları, 1970.

[29] Sütaş, İ., Öztaş, G., Karayolu İnşaatında Uygulama ve Projelendirme, İstanbul: TKY, 1986.

[30] NCHRP, Review of Truck Characteristics as Factors in Roadway Design-505, TRB, Washington DC, 2003.

[31] Transit, State Highway Geometric Design Manual Section 4: Horizontal Alignment, New Zealand, 2005.

[32] Yayla, N., Karayolu Mühendisliği, İstanbul: Birsen Yayınevi, 2009.

[33] Khanna, S., Justo, C., Highway Engineering, Roorkee: Nem Chand & Bros., 2011.

[34] Kök, B., Karayolu Mühendisliği ve Tasarımı, Ankara: Nobel, 2019.

[35] Cebon, D., Handbook of Vehicle-Road Interaction, Lisse: Taylor & Francis, 2000.

[36] Chowdhury et al, Are the criteria for setting advisory speeds on curves still relevant? ITE Journal Feb., 1998

[37] AASHTO, A Policy on Geometric Design of Highways and Streets, 7th Ed. 2018.

[38] Donnell, E., Wood, J., Himes, S., & Torbic, D. Use of Side Friction in Horizontal Curve Design: A Margin of Safety Assessment. Transp. Research Record, 2588(1), 61-70, 2016.