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Side Friction for Superelevation on Horizontal Curves

Executive Summary Report Volume I

C. C. MacAdam
P. S. Fancher
L. Segel

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16. Abstract <p>The basic objective of this study has been to address the issue of how adequate point-mass representations are in predicting friction requirements for actual vehicles operating along superelevated curves. The project focused on this and related questions by combining computer analysis and full-scale vehicle testing. Simple-to-use models for predicting the friction factor requirements at individual wheel locations were first developed and applied to the steady-turning condition. An existing comprehensive computer model used for predicting transient or nonsteady maneuvering situations was also employed to analyze friction demand while maneuvering along superelevated curves. Highway tests were then performed for two passenger cars and a five-axle tractor-semitrailer to collect representative test data and assist in validating the predictions of the computer models. Finally, a sensitivity analysis was performed to illustrate the relative importance and interactions of various vehicle parameters and highway geometrics in influencing side friction requirements.</p>					
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INTRODUCTION

This document is the Final Executive Summary Report for the Federal Highway Administration project entitled, "Side Friction for Superelevation on Horizontal Curves," performed under Contract Number DTFH61-82-C-00019. The basic objective of the project has been to address the issue of how adequate point-mass representations are in predicting friction requirements for actual vehicles operating along superelevated curves. Since current design practice characterizes the vehicle under conditions of steady turning motion as a simple point-mass, legitimate questions concerning the friction requirements at individual wheel locations and how they relate to the point-mass representation are examined.

The project focused on this and related questions by combining computer analysis and full scale vehicle testing. Simple-to-use models for predicting the friction factor requirements at individual wheel locations were first developed and applied to the steady turning condition. An existing comprehensive computer model used for predicting transient or non-steady maneuvering situations was also employed to analyze friction demand while maneuvering along superelevated curves. Highway tests were then performed for two passenger cars and a five-axle tractor-semitrailer to collect representative test data and assist in validating the predictions of the computer models. Finally, a sensitivity analysis was performed to illustrate the relative importance and interactions of various vehicle parameters and highway geometrics in influencing side friction requirements.

In addition to the Executive Summary Volume, the final report is comprised of two additional volumes. Volume II contains the main body of the technical report. Volume III contains Appendices A-G which provide detailed information relating to the computer models / predictions and experimental measurements.

CONCLUSIONS

The research conducted within this study has led to a number of conclusions which are based largely upon findings of computer model predictions and full scale vehicle test results gathered during the course of the project.

- * Steady turning models and vehicle tests have shown that significant differences do exist in wheel-to-wheel friction factor values on most vehicles during steady turning maneuvers along superelevated curves. Passenger cars and other two-axle vehicles exhibit the least wheel to wheel variation; commercial vehicles having multiple axle suspensions and elevated mass centers exhibit the greatest dispersion.
- * The level of variation in individual wheel friction factors considered and observed in this work indicated there was no significant evidence or finding that vehicles, or driver/vehicle systems, are less stable or otherwise adversely affected by this particular phenomena during steady turning maneuvers along typical superelevated highway curves.
- * No substantive evidence regarding friction factor dispersion was identified to conclude that current highway curve design practice, based upon a point-mass formulation, should be modified to accommodate the observed wheel-to-wheel variations. For example, alteration of the standard design equation to account for larger friction factor values derived from an individual wheel analysis, is not seen as necessary. These conclusions apply to horizontal curve negotiation after completion of the curve transition. Temporary disturbances to driver-vehicle systems during entry in to horizontal curves and due to different curve transition designs were not included in this study.
- * Computer analysis of low friction conditions for steady turning maneuvers on superelevated curves suggests that a tire/road

friction level approximately equal to the point-mass value is sufficient to permit stable driver/vehicle curve negotiation for passenger cars. However, for the 5-axle tractor-semitrailer used in this study (and presumably similar commercial vehicles), a minimum friction level approximately 10% higher than the point-mass value was generally necessary to guarantee stability for the same maneuver and low friction operating conditions.

- * Obstacle avoidance maneuvers simulated along an AASHTO design curve under low friction conditions showed that the minimum tire/road friction level necessary for stable execution of the maneuver is approximately equal to the peak friction value required of a point-mass object undergoing the same maneuver under adequate friction conditions. Therefore, even though certain tires on a vehicle may saturate for short periods of time during a low friction obstacle avoidance maneuver, the driver-vehicle system is able to maintain stability if the minimum tire/road friction level is at least as great as described above. This "rule of thumb" for estimating the minimum friction level needed for such maneuvers applied more or less equally to the passenger car and tractor-semitrailer vehicles used in the study.

- * Steady turning computer models developed during the project are viewed as reliable predictors of steady turning vehicle performance along superelevated curves. The models were employed to calculate individual wheel friction factor requirements for steady turning motion of passenger cars and commercial vehicles. The predictions from the steady turning models were shown to compare favorably with vehicle test data collected during the project and calculations from other comprehensive computer models. Use of these models is recommended for more in-depth analyses of vehicle / highway interactions as part of the highway curve design process.

- * Experimental identification and estimation of individual wheel friction factor values was shown to be possible but not highly

accurate and repeatable. The methodology employed in this project relied on direct measurement of vehicle responses and derivation of the friction factor values from this information. (Direct measurement of tire forces or wheel loads are not currently possible due to the limited accuracy and signal variability of such transducers that are available.)

- * Estimation of individual wheel friction factors through the use of steady turning models and representative vehicle parameters is viewed as sufficiently accurate and reliable for most vehicles. Further experimental validation efforts are not seen as necessary since the sensitivity analyses conducted here failed to identify significant adverse effects attributable to modest variations in wheel-to-wheel friction factor values.

- * Concerns occasionally expressed in the technical literature about steering reversal requirements by drivers along superelevated curves during conditions of reduced speed are not supported by the analyses and observations conducted within this project. Rather, steering reversals (up the slope) away from the direction of turn, even at very low speeds, are not viewed as generally possible for the great majority of passenger cars and commercial vehicles. Consequently, highway curve designers can use higher rates of superelevation on AASHTO curves without being concerned that lower speed vehicles may require steering motion "up the slope" and away from the direction of turn.

- * Mild oscillatory steering behavior and accompanying path curvature variations during steady turning maneuvers were observed in the test data collected in this study. The magnitude of steering oscillations observed during each curve negotiation, well after completion of the transition, was generally small (see Sections 6.6 and 7.1). Consequently these measurements do not suggest a need to modify existing AASHTO horizontal curve design practice based upon observations of driver-vehicle behavior on curves of fixed radius. Other studies, cited and discussed in

Chapter 7, have observed much greater levels of oscillatory driver-vehicle behavior but almost exclusively during entry transitions to horizontal curves.

- * The issue of spiral transitions and associated benefits, while not specifically studied or addressed within this project, was frequently encountered during this study. The transitions to each of the curve sites in the test program were not spirals but superelevated tangents, and as such, generally required mild counter-steering and subsequent overshooting of steering responses upon entry into each curve, especially with the tractor-semitrailer. This type of transition design necessitates the above described behavior which runs counter to the more natural driving process of requiring steering displacements in the direction of the anticipated turn. Use of spiral transitions to 1) introduce curvature and superelevation in a manner consistent with driver expectations, and to 2) retain the simple physics of the standard design equation, is supported.

RECOMMENDATIONS

- * Recommendations for improving the accuracy and repeatability of the experimental approach used in this work include:
 - use of additional sideslip trolley devices per vehicle
 - improved fore/aft positioning of these devices at or near specific wheel locations
 - use of ground-based roll motion transducers to better estimate side-to-side vertical load transfer

- use of optimal (Kalman) filtering techniques during data processing to improve estimates of the measured vehicle responses

* Future vehicle or highway studies considering the use of a sideslip trolley are encouraged to do so based upon the experiences of this project. However, design modifications have been recommended to improve its ruggedness for normal highway travel and to lessen its noise level due to normal road disturbances.

* Preservation of the driver/vehicle test data collected during this project in a standardized format for future reference is recommended. This data could be used as a useful source of representative driver/vehicle responses for further studies of highway curve design.