Papers

TIRE-VEHICLE SYSTEM ELEMENTS BEARING ON THE PROBABILITIES OF LOSS OF CONTROL

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As a means of clarifying the role of vehicle and tire factors in the skidding process, the interrelationship of the tire-vehicle system with the driver-vehicle-roadway system is examined. This examination shows that it is not possible to isolate "friction demand" and "friction available" as separate, distinct entities but that it is feasible to identify "skidding" as a loss of control event in which the "maneuver outcome" departs from the "maneuver demand." The various tire and vehicle design and operational variables governing the probability of skidding (as defined) are identified. The resulting perspective of "skidding" as a "potential for loss of control" is used as the basis for discussing counter-measures and to comment on trends in vehicle morphology likely to impinge on this potential.

Although it is generally acknowledged that poor "road grip" is the primary variable promoting the onset of "skidding," the role of individual tire-vehicle-system elements in the so-called "skidding" process remains to be established in a definitive, quantitative manner. In this paper, we wish to give an overview of the vehicle and tire factors involved in "skidding" in order to set the stage for the "tire and vehicle component" papers to follow. This overview will, however, be made in the context of the total driver-vehicle-roadway (D-V-R) system. Questions, such as "What is skidding?" and "How does it arise?", will be addressed as a means of clarifying the specific roles played by tire and vehicle factors.

In order to accomplish this objective, the paper first examines, in some detail, the traditional concept of "skidding" as a manifestation of insufficient tire-road friction available to meet a given "frictional demand." The D-V-R system is identified in block diagram form to show how this concept can be given more rigor. In so doing, we distinguish between design and operational variables as factors governing "skidding" or, more correctly, as factors governing the "potential for loss of control." The point is made that "skidding" or "loss of control" is a random event in which the probability of occurrence has some minimal value and increases above some minimum, depending upon

1. Drivers—their prudency and/or aggressiveness in pursuing their travel objectives,
2. Roadways whose properties are variable over space and time,
3. Vehicles and vehicle components varying in design, mechanical condition, and usage, and
4. The weather.

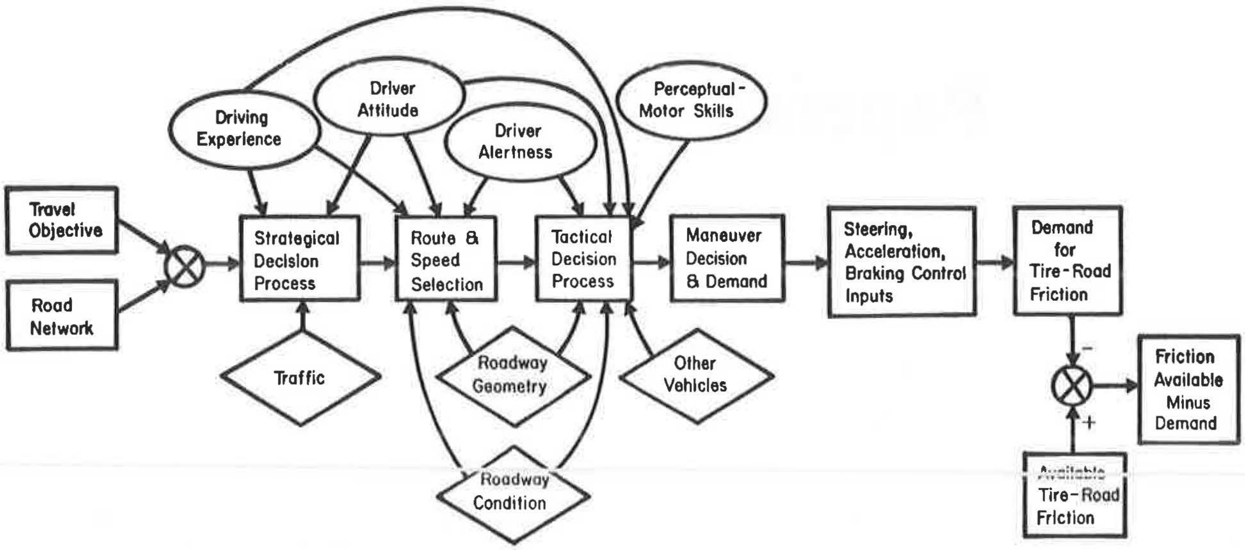
Given that the paper can successfully argue that "skidding" is a phenomenon which is essentially probabilistic in nature, it follows that "skidding" can never be totally prevented. Rather, it will only be possible to reduce the probability of its occurrence. Means, or countermeasures, for doing same are discussed, in this light, for tire and vehicle system factors only.

The Concept of "Friction Demand Versus Friction Available"—Is It a Viable Concept?

Figure 1 postulates the process by which a driver chooses a route and speed to satisfy a given transportation objective. In addition to the indicated long-term "guidance" activity, the figure implies that both roadway variables and driver variables influence the short-term control actions of the driver as dictated by the geometry of the roadway, the presence of other vehicles, and driver decisions with respect to controlling his vehicle in both time and space. Figure 1 implies that the driver continually makes choices with respect to the control actions needed to accomplish his maneuver decision, namely, the decision to execute a given trajectory.

In this context, it is reasonable to postulate that the "maneuver decision" constitutes a "maneuver demand" which, in turn, requires that forces be generated at the tire-road interface in order to accelerate the vehicle. Many investigators (most notably, Kummer and Meyer (1) as pioneers in the field) have found it convenient to identify this "maneuver demand" as a demand for tire-road friction levels which are sufficient to generate the required forces. In so doing, the problem of specifying a level of pavement "skid resistance" to satisfy the "maneuver demands" made by a representative population of drivers is, presumably, greatly simplified.

Figure 1. The driver-vehicle-roadway system involved in the maneuvering process.



Admittedly, Figure 1 constitutes an appealing definition of the "skidding" scenario. For the members of the highway community who are charged with designing and maintaining pavements that will exhibit adequate levels of friction during wet weather, Figure 1 suggests a reasonable way to get a "handle" on the problem. The envisioned methodology consists of several steps, viz.:

1. For a given section of highway, characterized by a specific set of geometric and traffic conditions, establish the distribution of accelerations that drivers employ in negotiating that section of roadway.
2. Assume that this acceleration behavior constitutes an acceleration "demand," thereby permitting a distribution of accelerations (however established) to be transformed into a distribution of friction levels, as required to sustain these acceleration levels.
3. Develop a means for objectively characterizing the frictional quality of a road surface and relate this "friction numeric" to the friction levels established in step (2).

This interpretation of Figure 1 constitutes for many people the essence of the "skid prevention" problem. Certainly, it has great intuitive appeal. Nevertheless, it does not come to grips with several questions, viz.:

1. What is meant by "skidding?" Is this phenomenon merely a manifestation of an inadequate level of pavement friction during weather conditions in which tire-road grip will necessarily be degraded?
2. How does one correctly transform an acceleration distribution into a distribution of tire-road friction levels, given that tire-vehicle systems operating on our road networks have a wide range of properties influencing this transformation?
3. Is "friction," per se, an adequate concept for dealing with tire-road grip?
4. Is the "demand for friction" independent of so-called "available" friction? Is the level of pavement friction "available" to tire-vehicle systems independent of the characteristics of tire-vehicle systems and also independent of the prevailing "demand?"

By raising these questions and by attempting to answer them, we can, hopefully, determine the extent to which the concept of "friction demand" versus "friction available" has utility. In addition, we wish to identify, as best we can, the manner in which the properties of tire-vehicle systems enter into a control process in which drivers find that they are unable to perform the maneuver that they intended.

Let us, first, consider the word "skid." Webster's Collegiate Dictionary defines the intransitive verb "skid" as (1) "to slide without rotating (as a wheel held from turning while a vehicle moves onward)," (2) "to fail to grip the roadway; specifically, to slip sideways on the road." The first definition seems to apply to a braking maneuver in which the wheels are not rotating, i.e., wheels are "locked"; and the second definition suggests a cornering maneuver in which the vehicle is sideslipping relative to the roadway. It can be argued that "sliding" and "slipping" motions are not undesirable, per se; however, they are undesirable when their occurrence prevents a driver from maintaining control over his path so as to accomplish a desired trajectory.

Examination of the dictionary definition of "skid" suggests that this is precisely the meaning that the word "skid" is intended to convey, namely, an inability of the driver to exercise control. If wheels are locked during braking, the vehicle may still be stopped in a successful manner. Nevertheless, the driver is not in control of his trajectory. Similarly, "a failure to grip the roadway" implies that a driver cannot exercise steering control so as to maintain his vehicle in a given lane. Thus we are suggesting that "skid prevention" is not the prevention of "sliding" and "slipping" motions, per se, from occurring on the roadway, but rather the prevention of incidents in which drivers cannot exercise control over their position in space and time. As suggested earlier, "skid prevention" must realistically be interpreted as the reduction of the probability that drivers will lose control over their path, particularly when roadways with degraded frictional qualities must be negotiated.

If Figure 1 is expanded to account for the physics of the tire-vehicle system which are involved in performing maneuvers on the roadway, Figure 2 is obtained. Figure 2 shows only the right-hand side of Figure 1 in which the "friction demand" and "friction available" blocks have been replaced by a block-diagram representation of the process by which maneuvering is accomplished. The outcome departs from the maneuver demand, "loss of control" has been encountered. Alternatively, we could say that "skidding" has occurred.

If we ask what has specifically transpired such as to cause the maneuver outcome to depart from the desired trajectory, one possible answer is that the driver did not generate the proper control actions. However, if we assume that the driver has sufficient experience and skill to "close the loop" around the vehicle and thereby modulate his control inputs so as to achieve the desired trajectory, then some other explanation must be offered. An explanation that is frequently offered is that the shear forces required to perform the maneuver could not be generated because the frictional coupling prevailing at each tire-road junction was

Figure 2. A block diagram of the tire-vehicle system involved in the maneuvering process.

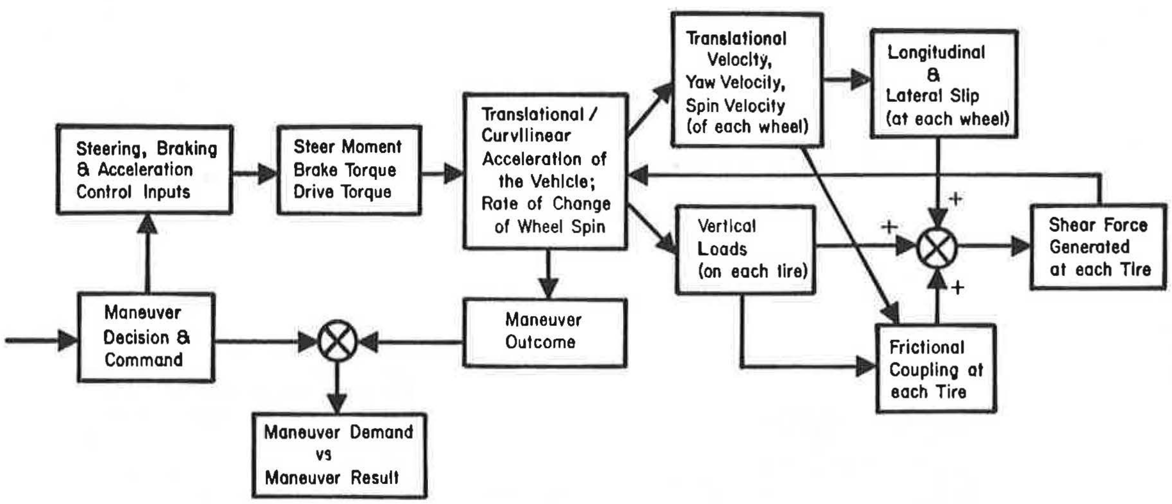


figure indicates that, in order to implement his maneuver decision, the driver steers, accelerates, or brakes (independently, or in combination), which control action results in moments and/or torques causing an acceleration of the total vehicle and/or angular acceleration of two, or more, wheels about their spin axis. These accelerations, integrated over time, result in a time-varying translational velocity and yaw velocity for the entire vehicle and in a time-varying spin velocity of each wheel. Simultaneously, the static loads on each of the wheels (tires) are continuously being redistributed during the course of the maneuver. The translational and angular velocity of the entire vehicle, together with the spin velocity of each wheel, determine the lateral and longitudinal "slip" at each wheel (where "slip" has a specific kinematic meaning). These individual wheel "slips," together with the prevailing vertical loads and the frictional coupling prevailing at each tire-road junction, determine the shear force that can be and is generated at each tire. These shear forces (summed over all tires) continuously feed back on the system, and thereby determine the accelerations produced by the control inputs initiated by the driver. To the degree that the maneuver outcome agrees with the maneuver decision (or maneuver demand), the driver has control over his vehicle. To the degree that the maneuver inadequate. (Note that Figure 2 uses the phrase "frictional coupling" because this coupling is speed and vertical-load dependent, as well as being dependent on tire factors which can be different from tire to tire.) However, on examining Figure 2 further, we see that it is impossible to isolate "friction demand" and "friction available" as separate entities or concepts. For example, it is not possible to treat the instantaneous frictional coupling indicated for each tire as a single "available friction" because of the above-mentioned load dependency and also because operational vehicles frequently possess tires which are asymmetrical (either fore/aft or right/left) in properties influencing their coupling to the roadway. Further, the existence of a center of mass at a finite height above the roadway results in asymmetric loadings such that the maximum levels of braking and cornering acceleration (in g units) achievable without (1) wheel lock or (2) "ploughout/spin," respectively, is significantly less than the coefficient of peak friction characterizing the specific tire-road combination involved. This state of affairs holds for the case in which the driver performs as a perfect (ideal) controller, with even lesser levels of braking and cornering acceleration being attainable in practice, due to the inability of the human operator to close the vehicle control loop in an ideal or perfect manner (2, 3).

Since the process of "demanding" and generating shear forces to accomplish a maneuver is, in fact, a closed-loop process, it is not at all clear as to how one might break into this loop for purposes of identifying a "friction demand" and the "friction available." It is, however, feasible to speak of "loss of control" as a phenomenon in which the acceleration history achieved in a given maneuver is different from the acceleration desired by the driver.

Operational and Design Variables—Factors Governing the Potential for Loss of Control

Notwithstanding the inadequacy of Figure 1 in defining a "friction demand," it does indicate how driver and roadway variables can and do influence the distribution of acceleration demands. These influences are being addressed by others at this conference. In this paper, we are only concerned with identifying the process by which tire-vehicle-system properties influence the probability of drivers being able to maneuver as desired on a given roadway surface.

Figure 3 consists of Figure 2 with several blocks added to indicate how vehicle factors, roadway factors, and external disturbances (other than driver control inputs) influence the maneuvering process. Before discussing these factors (item by item), it is worth emphasizing that the potential for loss of control of a given vehicle depends on factors in addition to tire traction qualities and brake system characteristics. This is not to say that the latter two items are not major. They undoubtedly are. However, it shall be argued that the variability (or randomness) in encountering a loss of control event derives from variability in many other vehicle factors, as well as the variability which may exist in (1) tire traction levels and (2) braking system characteristics.

Consider the vehicle factors which influence the forces and moments generated by driver-control inputs. A passenger car can be accelerated by means of drive torque applied either to the front wheels, rear wheels, or all four wheels. Clearly, the consequences for skidding vary with each design. Further, the level of torque that an engine can generate relative to the weight carried on the drive wheels will influence the probability of spinning the driving wheels, particularly when the vehicle is being operated on a pavement with reduced frictional qualities. Analogously, brakes that are very effective (thereby requiring lower levels of pedal force for their operation) will likely lead to higher probabilities of wheel locking than would otherwise be the case. To the degree that the fore/aft proportioning of brake torques per unit applied pedal force varies from

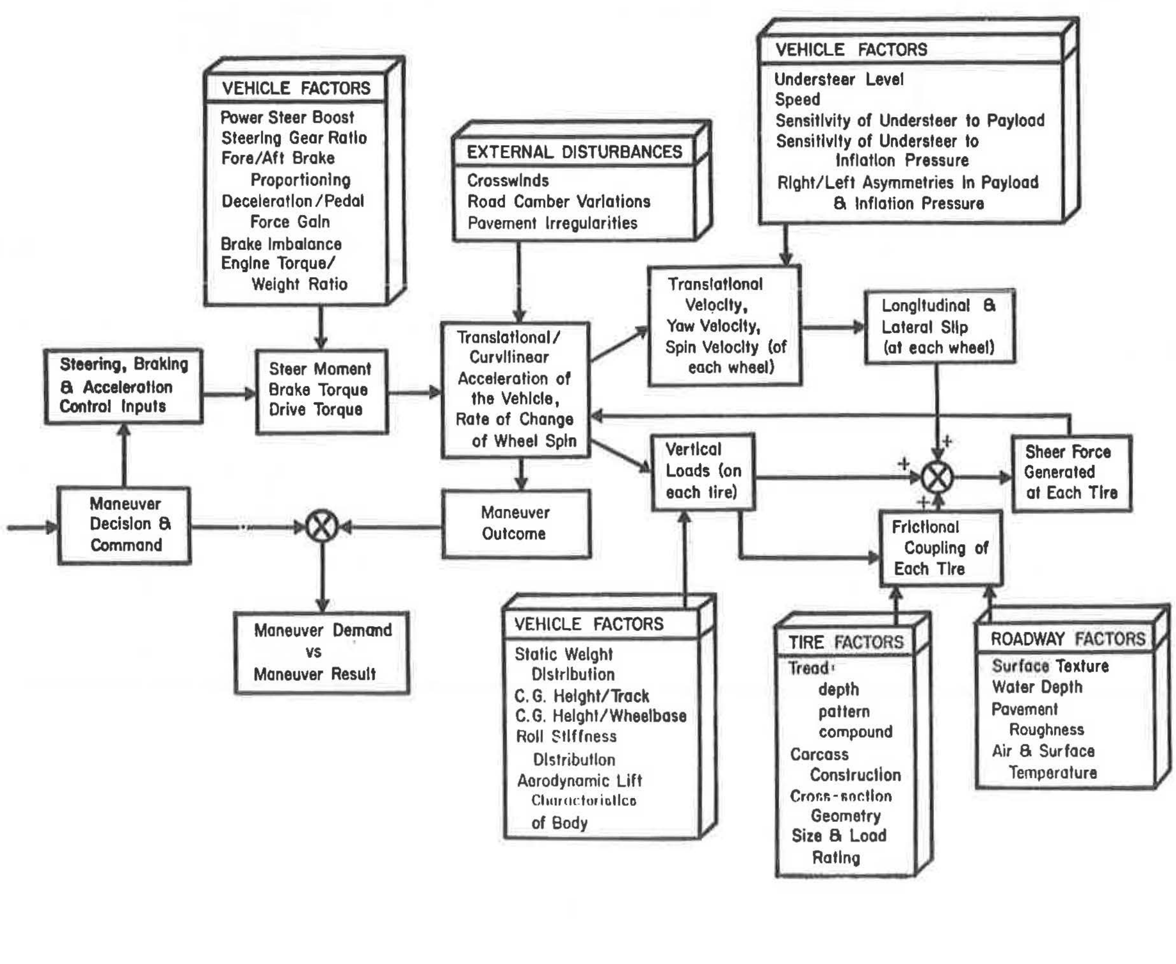


Figure 3. Tire-vehicle-roadway factors influencing the maneuvering process of the tire-vehicle system.

vehicle to vehicle, we can expect to find variations in braking efficiency (4) and, consequently, on a given road surface, we would expect wheel lock (or skidding) to occur at different levels of deceleration. Since brakes, i.e., mechanical friction devices, tend to be variable in effectiveness, vehicles frequently exhibit right/left asymmetries in the locking of wheels when stops or decelerations are made on reduced-friction surfaces. Clearly, the installation of sensing and actuating systems acting to prevent wheel locking during braking will have a very marked influence on the skidding potential of the motor vehicle. More on this point later.

Figure 3 indicates that the motor vehicle responds to external disturbances as well as to driver control. These external disturbances can occur both randomly and systematically in space and time. For example, the topography of the road and prevailing weather conditions may combine to produce an area marked by high crosswinds. Under these circumstances, we should expect the potential for loss of control to increase over and above the level prevailing in still air and to be higher yet if the pavement is wet. Similarly, disturbances deriving from the longitudinal and lateral profile of the roadway pavement might be insignificant when a vehicle is traversing a high-friction surface, with the opposite being true when the pavement exhibits a reduced level of friction.

To the degree that the steady-turning response and the dynamic yaw response to steering inputs influence the manner in which the driver exercises control over direction and lateral position (e.g., influences the amount of overshoot in yaw and sideslip accompanying a rapid lane change), the potential for loss of control should vary. Accordingly, Figure 3 lists several factors which influence the static and dynamic directional response of the motor car. Although the factors listed—understeer, speed, etc.—may have only modest implications for increasing the potential for skidding on high friction pavements, they are likely, in a synergistic way, to have a significantly greater importance when maneuvers are being performed on reduced friction surfaces. It should be noted that these factors imply that the motor vehicle is a highly variable mechanical entity depending on how the vehicle is operated and maintained.

Prior to considering the factors that impinge directly on the frictional coupling mechanism, we should observe that the morphology (i.e., the structure and form) of the motor vehicle has a very marked influence on the manner in which normal loads are distributed (from tire to tire) during a maneuver. The physics of four-wheeled vehicles (employing identical tires on each wheel) are such that cars with substantially forward- or rearward-biased weight distributions will exhibit, on dry road surfaces, lower levels of peak turning ability than will cars with a center of mass located (approximately) at mid-wheelbase. The validity of this statement derives from the tendency of tires to exhibit lower frictional coupling, that is, less shear force per unit normal load, as load is increased on a dry surface (5, 6) and the further requirement for a yaw-moment balance during a steady turn. (It is not known whether this statement is also generally true for vehicles operating on wet road surfaces.) Accordingly, Figure 3 lists the first-order variables governing wheel loads during braking, accelerating, cornering, and combined maneuvers. In addition to these first-order variables, there are many second-order variables of influence (e.g., roll center heights). Both these first- and second-order variables vary widely over the total vehicle population. Accordingly, we should expect that the potential for skidding on reduced-friction surfaces would differ from vehicle to vehicle even if the frictional coupling between tire and pavement were the same for all vehicles and all tires.

As implied by Figure 3, the maneuver outcome will differ from the maneuver demand if, and when, the shear forces generated at each tire are inappropriate for providing the required forces. Further, the driver will not be able to exercise precise control over his trajectory if, and when, the tire shear forces reach an upper bound, as limited by the prevailing frictional coupling. Clearly, the potential for loss of control is directly and markedly influenced by those factors which govern the frictional coupling between tire and road. In this context, Figure 3 identifies roadway factors, as well as vehicle factors, since the two sets of factors interact so strongly. During the course of this conference, much will be said about how these factors influence the friction couple. A point worth making, in the context of this presentation, is that the tire factors identified in Figure 3 can vary significantly from wheel to wheel. In particular, the existence of fore/aft asymmetry in frictional coupling between tire and road will not only impact on the maneuver level that can be sustained by a given road surface, but will also impact significantly on the trajectory that will ensue when a maneuver is attempted that is more severe than the road surface can sustain. Although roadway factors influencing frictional coupling may be variable from tire to tire (e.g., as a result of puddles), this variability will be highly random in time and space. On the other hand, tire factors have a fixed pattern of variability for a given vehicle, but these patterns vary considerably from vehicle to vehicle in a highly random manner.

This review of vehicle and tire factors shows that the factors influencing the manner in which the maneuver result departs from the maneuver demand fall into two major categories. On a given road network, the potential for loss of control varies randomly because of differences in design properties prevailing within the total tire-vehicle system population prior to any changes or alterations being induced by use. On the other hand, a second major source of variability derive from operational (i.e., vehicle-in-use or tire-in-use) factors. An overall assessment of these two sources of variability suggests that operational or in-use variables are likely to be far more consequential in controlling the potential for skidding than differences in design practice. Nevertheless, we can anticipate that the presentations to be made on "Vehicles, Tires, and Other Vehicle Components" will emphasize facts and design features which bear on the performance of a component or vehicle in its new or pristine state.

Countermeasures for Reducing the Potential for Skidding

Given that design and operational variables vary in a random fashion and also combine in a random fashion to create an ever-existing potential, or probability, for loss of control events, countermeasures should be sought primarily to reduce this probability. During this conference, each element of the D-V-R system is being addressed and the state of the art available to reduce the contribution of drivers, vehicles, and roadways, respectively, to skidding is being examined in great detail. My objective, here, is strictly one of identifying, from an organized perspective, future problems and countermeasures applicable to the vehicle component of the D-V-R system.

Let us refer to Figure 3 and consider again the vehicle and tire factors which influence the outcome of the maneuvering process. We see that the block of vehicle factors influencing the steer moment, drive torque, and brake torque created by the driver are factors which bear on the ease with which the driver can control his vehicle, namely, they influence the ability of drivers to modulate their control inputs and thereby generate forces for maneuvering appropriate to the circumstances that prevail. To the degree that knowledge exists with respect to how the indicated factors influence the ability of drivers to minimize the occurrence of wheel spin or wheel lock, these factors can and should be integrated into the design process.

In this context, the use of antilock braking systems would constitute:

1. A recognition of the large difficulties encountered in modulating brakes on slippery surfaces, and
2. A decision to take this very difficult task away from the driver.

Further, it would appear that the antilock countermeasure has substantial face validity. However, there is a cost penalty which is non-trivial. It follows that the voluntary purchase, or mandatory use, of antilock braking systems poses a complex safety-economics issue that cannot, at this point in time, be readily resolved in an objective manner. Notwithstanding our inability to resolve this kind of safety-cost tradeoff in an objective manner, it would appear that factors which influence vehicle controllability should be critically examined during the design process. Particular attention should be given to the ergonomic implications of these design variables (listed in the first block in Figure 3) in increasing or reducing the potential for loss of control.

When the frictional coupling existing at the tire-road interface is lowered at a particular point in time and space, there is an increased probability for external disturbances to lead to a loss of control event. Countermeasures to reduce the impact of disturbances (other than driver-initiated inputs) can, of course, be introduced by appropriate design and maintenance of the traveled way. The vehicle designer, on the other hand, deals with the task of minimizing the response of the motor car to the external disturbances tabulated in Figure 3. In this latter context, it is worth noting that the growing pressures to increase the efficiency of motor vehicles will, in all likelihood, lead to motor cars characterized by increased ratios of side area to weight. This means that the average car of the future will be more sensitive to crosswinds, rather than less. Moreover, the point can be made that the potential for loss of control, as exhibited by a highway transportation system, depends, in part, upon the morphology of the existing population of motor vehicles. Future trends in vehicle morphology could, conceivably, go in the direction of increasing this potential rather than the other way around.

As pointed out earlier, the second group of vehicle factors tabulated in Figure 3 influences the static and dynamic response of the motor car to steering control. It follows that driver closure of the control loop, as evidenced by the steering precision exhibited by a driver-vehicle system, is similarly affected. However, there is no reason to believe that the large number of constraints controlling this particular aspect of vehicle design results in a design practice which compromises driver-vehicle system behavior on reduced-friction surfaces. On the other hand, there is considerable opportunity for vehicle owners and drivers to load and "tire" their cars such as to change, in a rather drastic manner, the understeer levels designed into the "as-new" vehicle. Although it is proper to point out that this particular vehicle-in-use process, specifically, the degradations in handling that result (for example, from tire-in-use factors), is a universally negative feature of an operating highway transport system, it should also be noted that this feature may be particularly consequential when, and if, the operating scenario is characterized by reduced frictional coupling at the tire-road interface. Accordingly, countermeasures serving to constrain the opportunities for users to move their vehicles out of the directional performance space sought by the designer seem to have face validity with respect to reducing the overall potential for loss of control. Taking positive steps, in this context, is difficult, however, in that the control process involved is considerably more complex (and less objectively defined) than, for example, the manner in which tire and roadway factors impinge directly on the frictional coupling process.

Design factors influencing the redistribution of loads among the wheels of a maneuvering motor vehicle are also highly constrained. Instead of opportunities to optimize this redistribution for minimizing the loss-of-control potential, it appears that the growing pressure for smaller, more efficient cars will lead to a vehicle population with shorter wheelbases and lesser track widths. This trend will, in turn, mean increased maneuvering-induced loads and reduced maneuvering limits on dry roads and perhaps on wet roads as well. Further, it should be observed that whereas aerodynamically-induced lift forces are always undesirable from the standpoint of the road gripping mechanism, they can become a more significant contributor to the potential for loss of control, if and when the average weight of the vehicle population is reduced. Naturally, the importance of this mechanism depends upon future travel speeds and the extent to which designers will take pains to (1) minimize the lift coefficient of car bodies or, perhaps, (2) develop shapes with a negative lift coefficient.

The tire factors identified in Figure 3 as bearing directly on the frictional coupling between tire and road will be discussed at length in this conference. It will be pointed out that there are many tire design features which influence the ability of the tire to grip the road, particularly in the presence of water and other contaminants. Further, it will become clear that the tire design process is highly constrained such that one cannot opt for road-gripping qualities at the expense of other requirements and qualities. The point to be stressed here is that incremental improvements in wet-road gripping qualities of new, fully-treaded and properly inflated tires are gradually diminished by the process of tread wear. Even more important to the maneuvering process are fore-aft and side-to-side differences in tread depth, not to mention differences in frictional coupling which derive from the mixing of tread patterns, carcass construction, etc. This is not to imply that changes in the operational state of the installed tires, as controlled by the owner (user) of a motor vehicle, are critical, but merely to point out that the ability of driver-vehicle systems to utilize the inherent road-gripping qualities of tires is influenced by the differential character of the installed tires. In general, it may be stated that the potential for loss of control is influenced by the random distribution of tire states (tread depth, tread patterns, etc.) as occur in a population of operating (or in-use) vehicles. Countermeasures seeking to minimize the potential for skidding by means of tire design and/or selection must necessarily give attention to the tire-in-use process, since vehicle lifetimes are significantly greater than the lifetime of tires.

To conclude, this author is not aware of any analysis which permits one to deduce and/or predict, in quantitative terms, the influence of tire-vehicle system elements on the probability for skidding (i.e., loss of control) in an operating highway-transportation system. It follows that it is not possible to deduce, in an objective manner, how effective any specific design or operational countermeasure will be in reducing the overall probability of a "skid" event. Needless to say, if the effectiveness of countermeasures cannot be determined, we cannot perform cost versus effectiveness studies much less benefit versus cost studies. On the other hand, we do understand (in qualitative terms) how various elements and factors within the tire-vehicle system influence the potential for skidding such that choices <u>can</u> be made, particularly when the financial consequences are not significant or when the decision does not disturb the degree to which other requirements or constraints are satisfied.

References

1. H. W. Kummer and W. E. Meyer. Tentative Skid-Resistance Requirements for Main Rural Highways. National Cooperative Highway Research Program Report 37, Highway Research Board, 1967.
2. L. Segel and R. Mortimer. Driver Braking Performance as a Function of Pedal-Force and Pedal-Displacement Levels. 1970 International Automobile Safety Conference Compendium, Society of Automotive Engineers, New York, pp. 159-178.
3. A. L. Alexander. Braking Performance of Cars with Different Brake and Weight Distribution. Road Research Laboratory (Crowthorne, England) Report LR 130, 1967.
4. J. A. Rouse. The Distribution of Braking on Road Vehicles. Proceedings of the Symposium on Control of Vehicles During Braking and Cornering, Institution of Mechanical Engineers, London, June 1963.
5. S. Mercer, Jr. Locked Wheel Skid Performance of Various Tires on Clean, Dry Road Surfaces. Highway Research Board Bulletin No. 186, 1958, pp. 8-25.
6. R. D. Ervin and C. B. Winkler. Braking Efficiency Test Techniques. Final Report on Contract DOT-HS-031-3-765, Highway Safety Research Institute, The University of Michigan, December 1974.