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Coefficients of Friction and Automated Freeways

Anthony Hitchcock

California PATH
University of California, Berkeley

February 1994
This work was performed as part of the California PATH Program of the University of California, in cooperation with the State of California Business, Transportation, and Housing Agency, Department of Transportation; and the United States Department of Transportation, Federal Highway Administration.

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ABSTRACT

This paper sets out some simple facts about the effects of the interaction between tires and the road insofar as it affects braking and forward acceleration. No originality is claimed - these are, in a simplified form results well-known to experts in the field. The paper rehearses these because the author has produced a number of papers about Automated Highway Systems which assume the validity of the ranges of numbers discussed here. In dry conditions, on a good road with good brakes, deceleration forces from tires to the road have a maximum value which cannot be relied on to exceed 0.75 or so. In the wet this number sinks to 0.45, and can be much less if the tires are worn.

Attention is drawn to the differences in the ways AHS carraigeways may wear, from those on present-day freeways, and the possible effects of these on braking capability.
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Introduction

What follows is a statement of existing knowledge, in the simplified form in which it is understood by the author, of the tire/road interaction insofar as it affects maximum rates of braking. It forms the background to assumptions made in a number of other papers by the present author. This is followed by some speculations of the effects on automated freeways, a field in which there is as yet no experience, and on which no specific research has yet been carried out.

This note also discusses some potential problems in the design and maintenance of the pavement contained in automated lanes on a freeway. The problems arise because the spatial patterns of use of the road surface differ on an automated lane from those on which experience to date has been gained.

It should be appreciated that the numbers discussed here are by not minimums. In the presence of ice or snow, much lower values are possible, and if there is flooding, or rain heavy enough to leave running water over the relevant part of the road surface, this can also be the case for some tire conditions. Both snow and the other conditions do arise regularly in some parts of the United States of America. This can also happen arise in California. What is done here is to set out the considerations on which design values can be selected, representing average performance in conditions which are poor, but nevertheless arise frequently. Adoption of these preliminary values has made research results comparable. Later, there may be a need to produce standard values against which performance of AVCS (Advanced Vehicle Control Systems) devices and systems can be assessed for evaluation.

The frictional forces which cause vehicles to come to rest when braked are least when there is ice or snow on the road. Since the application of Automated Highways - PATH’s main concern - will in the first place be to the more populated parts of California no great stress will be laid on these conditions. In other places, however, considerations of snow and ice would be central.

It should also be appreciated that it is not safe to use these numbers for purposes other than those intended, namely for calculating the maximum decelerations achievable by a car on an automated freeway. The interaction between tire and road is a complex non-linear
phenomenon. The figures here are, in particular, not applicable if it is wished to calculate the frictional forces involved in turning. Further, these decelerations are maximum values, assuming, therefore that the vehicle's brakes are in no way defective. If brake pads are worn, these accelerations may not be achievable.

There are of course other forces than friction which may slow down or accelerate a car than tire-road friction. If there is a gradient, gravity will have this effect. Aerodynamic forces will always tend to slow a vehicle down. Such forces are very variable: they depend strongly on speed and wind velocity. There are further complexities when vehicles are marshalled in platoons which are the subject of current research - at present we do not have even an approximate idea of the way they vary. We shall not consider these forces further here.

**Summary of Existing Knowledge**

The content of this section derives from the author's background knowledge, augmented by consultation with acknowledged experts in the field.

For the purposes we have here, it is sufficient to describe the tire-road interaction in terms of an effective coefficient of friction, which we will call \( f \). When the brakes are applied the maximum deceleration that can be attained is \( f g \), where \( g \) \((=10 \text{ m/s}^2)\) is the acceleration of gravity. \( f \) is affected by:

- whether the road is wet. Typical, dry values of \( f \), at the end of winter, with no wheel lock will be 0.6 or even 0.7. If there has been frost, which roughens the roadstone, higher values can be observed. In the wet, even with good tires and no wheel-lock, values of \( f \) after a frosty winter are unlikely to exceed 0.5. Wheel-lock can reduce these values by 0.1.

In addition to this reduction on wet roads, which is probably due to the lubricating effect of water, together with oil, rubber and other debris found on roads, there is another effect which can be very important. On a wet road the water has to move away before the tire can touch the road. Tires in good condition have grooves, "tread", into which the water can move. If there is much water and shallow tread there is not enough space for the water, and the water has to be squeezed out to the edge of the tire. The water has inertia, and it takes time for it to move in this way. The higher the speed, the more of it does not get out. The tire is then partly supported by the water, which will transmit no shear forces, and therefore cannot contribute to friction. Clearly this effect is greatest when the tire is quite smooth. For this reason \( f \) will be progressively reduced as speeds increase, if the tread is worn or absent. At higher speeds yet the tire may cease to touch the road at all, and friction is effectively reduced to zero. (Under these conditions a free wheel will cease to rotate, so small is the force exerted on it by the road.) This can happen at speeds less than the normal operating speed on a freeway, automated or not, if there is water sufficient to drown the road texture. This does not imply flooding or standing pools - if the road is superelevated (i.e., has banked corners) the transverse flow during heavy rain can be sufficient. As speeds increase, progressively less water is needed to cause such *hydroplaning*. 

It would be reasonable to assume that roads used for automated freeways are sufficiently well designed, constructed and maintained for full hydroplaning to be avoided. It would be less reasonable to assume that all vehicles have anti-lock braking, so that only rolling need be considered. However, even after a frosty winter, when road friction is at its best, it would be unwise to expect a good tire on a wet road to have a rolling $f$ of more than 0.5, while for a smooth tire one cannot expect $f$, rolling, to exceed 0.35.

- **Time of year.** In winter the action of water and cleans away debris, oil and rubber from the road. $f$ rises in both wet and dry conditions. If there is frost, there is another effect: the microtexture of the roadstone is restored, and $f$ rises yet further. In summer, the roads acquire a surface of oil, rubber and other debris. This reduces $f$. At all times the action of tires polishes the surface, reducing $f$, and in California, there will often be little frost to reverse this effect. In fall, when it first rains, the good-tire, no wheel-lock value of $f$ may be as low as 0.35, though it could be as high as 0.45. Without full hydroplaning, the poor-tire value can drop to 0.25.

- **Condition of tires.** In dry conditions, $f$ is essentially independent of tire tread (racing cars, in the dry, use smooth tires), but if the road is wet there is loss of contact with the road surface, as explained already. Further, as tires age, there are changes in their chemical composition which cause them to become less flexible. This can result in reduced values of $f$, particularly on wet roads.

- **Wheel locking.** In all conditions the rolling value of $f$ is greater than the sliding one. The effect is greatest when the road is wet or the surface loose, when the sliding value of $f$ may be as little as 75% of the rolling one.

The above applies to ordinary good-quality road surfaces, following good practice in choice of materials, methods of construction and maintenance. However, under exceptional circumstances artificial roadstone (usually calcined bauxite) in an epoxy resin matrix is used. Such a roadstone can have a dry, rolling value of $f$ of as much as 1.0. This high value is not very greatly affected by time of year, but is liable to similar percentage reductions in the wet with smooth tires as the others. The cost is 100 times or more the cost of normal surfaces.

**Choice of Reference Values**

It is possible, even in California for there to be such heavy rain that hydroplaning becomes with smooth tires at speeds below the 60-70 mph usually regarded as the normal operating speed of an automated freeway. Sometimes, too, it snows. In practice, under such extreme conditions, one would either close the facility or impose a vastly reduced speed and/or increased mean vehicle spacing. But such conditions are exceptional.

In California too, winter frosts cannot be relied on to counteract the effect of polishing, and the highest values quoted above are thus only applicable to freshly-laid surfaces. Some kind
of regular monitoring may be necessary to ensure that the effect of polishing does not accumulate excessively.

For standard operating conditions, the usual engineering practice would be to choose the worst conditions which would arise frequently. Thus smooth-tire conditions would be used unless a mechanism for testing tread depth on entry can be convincingly proposed. Equally, wet fall conditions would be appropriate. Again, one might propose a system which changed its operating parameters from month to month, or according to the weather forecasts (reliability?). Day-to-day (or hour-to-hour) variations in capacity in such a system could well span a factor of two or more, and there would be a need to study the safety and operability of the system as it changed.

At this stage such ideas have not been fully explored: it is far from clear that they make sense. Wet fall conditions have therefore been used as a basis for the author’s research in PATH projects.

**Road Surface Operation on Automated Freeways**

On an ordinary freeway, or a rural or urban arterial, lanes are 12 ft wide. Some people drive near the left edge, some near the right edge, most drive, in a car typically 5 ft 6 in to 6 ft 6 in wide, within 1 foot or so of the center. Wheel tracks are thus not spread quite uniformly, and if the road is examined carefully shortly before resurfacing a tendency for there to be a slight hump in the middle of the lane and at the edges is visible. Also, it is usually apparent to the touch that the depressed parts are smoother than the others. The depressed area is 2 feet or so wide. The depression is usually rather smaller on the leftmost lanes, where heavy trucks are fewer, but the polishing effect is less variable.

This reflects what is known about the effects of axle weight on road damage. The classical ASSHO tests of the fifties showed that damage to the basic structure of the road was proportional to the fourth power of axle weight. In the absence of trucks, therefore, such subsurface deformation of a well-built road would be negligible. Similarly a truck will cause disproportionately more surface deformation, and disproportionately more polishing, than a car. The disproportion, in either case, is probably not so great as with subsurface deformation. This was discovered in telephone consultation with Prof J. J. Henry of Pennsylvania State University.

On an automated freeway, the automatic lane keeping will ensure that vehicle centers usually remain within an inch or so of the lane center. Most cars will still be between 5 ft 6 in to 6 ft 6 in. The wheels will therefore follow the same course to within 6 in or so. All polishing will be concentrated in a narrow band, and be greater by some four to eight times than on a normal freeway. Further the automated lane will have a capacity some three times that of the other lanes. Its daily usage may be more or less than three times that of normal lanes, but if the automated freeway is not uneconomic, it will be exceed the present value considerably. The polishing effect will be made again greater in proportion.
There will therefore be some tendency to create narrow bands of polished road surface on automated lanes in the area where cars run. The bands may become slightly depressed, leading to the possibility that hydroplaning could occur. If a vehicle suffers some lateral control problems while partly on and partly off the bands there may be unexpected effects. What will happen on the untrafficked parts of the road is also unknown. If the depression is yet deeper and irregular there can be irregular twisting forces which destabilize lateral control.

Whether these effects are large enough to be important is unknown: the experts have advised that some preliminary testing would be advisable. By its nature such research is of long duration.

Acknowledgments.

This work was performed as part of the program of Partners for Advanced Transit and Highways (PATH) of the University of California, in cooperation with the State of California, Business, Transportation and Housing Agency, Department of Transportation, and the United States Department of Transportation, Federal Highway Administration and the National Highway Traffic Safety Administration.

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The author also wishes to acknowledge, with thanks, the valuable guidance of Prof. John A Deacon, University of Kentucky, of Prof J.J. Henry, Pennsylvania State University, and of Mr. Scott Baysinger of PATH.