Technical Note

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Effect of High Friction Surface Treatment on the Onramp Merging Length

Chiu Liu[1+] and Zhongren Wang[1]

Abstract: The pavement skid resistance, namely the vehicle tire-road contact friction, plays important roles on pavement response, pavement deterioration, traffic operation, and traffic safety. One may find higher tire-road friction surface course is needed or applicable as an effective safety countermeasure for reducing potential traffic crashes and/or collision severity at certain roadway locations, in particular, the ramp emerging or weaving area where foreseeable sideswipe or rear-end collisions might take place between a merging vehicle and another vehicle from the outside lane. A driver should decelerate when merging become difficult as trained in a licensing procedure for avoiding potential collisions. If the required deceleration length is shortened upon avoiding a potential collision, the number of collisions at the onramp should decrease and the collisions if occurred would be less severe. The tire-road frictional coefficient if raised high enough could dramatically reduce the required deceleration length prior to collision, and the high friction surface treatment (HFST) has been introduced in practice for the last decade to shorten the required distance to stop a moving vehicle for both wet and dry road surface conditions. It is of significant interest to examine quantitatively, based on a proposed integrated framework, the effect of a high frictional surface course on reducing the needed deceleration distance, in particular, on an onramp merging/weaving section constructed with limited right of way.

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***Key words**: High friction surface treatment; Onramp; Parameter; Merging length; Vehicle; Collision.*

Introduction

High friction surface treatment (HFST) on pavement surface is applicable on road curves, ramps, and even at spots where high friction is needed to avoid potential conflicts between vehicles and pedestrians. In particular, the HFST can be very useful for some onramp merging or weaving areas where the full lane section paved with conventional hot mix asphalt (HMA) or Portland cement concrete (PCC) was too short at least for a fraction of the onramp traffic to decelerate for emergency situations. It is expected safe merging implies that a driver on a short onramp finds the option to merge behind an adjacent vehicle in the freeway outside lane, and a merging section paved with HFST course will help the driver to decelerate to a low speed when merging ahead of the mainline traffic becomes difficult. Since the merging maneuvers involving two passenger vehicles are less critical than that involving a large vehicle and a passenger car, we examine the situation where the merging involved an onramp passenger vehicle and a heavy/large vehicle on the outside lane. In this scenario, the onramp vehicle may happen to be in the large blind area at the passenger side of the heavy vehicle possibly throughout the merging process. Under this circumstance, a passenger car driver would decelerate to avoid the potential conflict which could be fatal. Based on the physical framework established before [1, 2], the short design onramp length, depending on the frictional contact, should be reasonably long for an onramp driver to merge into the freeway traffic for some difficult merging scenario as shown in Fig. 1, in which the driver attempts to merge behind when the onramp vehicle is a bit ahead of the heavy vehicle in the outside lane. In this paper, the influence of the frictional coefficient on the onramp weaving length is examined and analyzed by taking into account various physical parameters associated with the merging as described in Fig. 1, including the traveling speed on the freeway outside lane.

[1] California Department of Transportation, 1120 N Street MS-36, Sacramento, CA 95814, USA.

[+] Corresponding Author: E-mail Chiu_Liu@dot.ca.gov

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Formulations

Denoting the onramp driver's perception-reaction time as δ, the onramp vehicle deceleration with respect to time t is written as

$$\frac{dv}{dt} = (\alpha - \beta v)\aleph(t-\delta) \tag{1}$$

where function $\aleph(u)$ is a step function; namely, $\aleph(u) = 1$ for $u > 0$ and, $\aleph(u) = 0$ for $u \leq 0$. Both phenomenological parameters α and β, depending on the frictional coefficient, are negative for deceleration [3-5] and can be fine-tuned to fit different contact characteristics derived from observations or test results. Physically, parameter α represnts the static skid deceleration. Deceleration is conventionally approximated with constant but actually varies with speed to some extent. The tire-road contact characteristics may change with speed partially because the contact surface is road-profile dependent and the magnitudes of the excited tire vibration modes depend the road profile. In Eq. (1), the frictional coefficient is approximated with a linear functional form of speed and β should be a relatively small quantity.

Integrating Eq. (1) yields the vehicle speed with respect to time

$$v(t) = V_R\aleph(\delta - t) + \frac{1}{\beta}\left[\alpha - (\alpha - \beta V_R)e^{-\beta(t-\delta)}\right]\aleph(t-\delta) \tag{2}$$

The onramp vehicle speed when the merging starts is denoted by V_R, which can be visualized as the speed with which the onramp vehicle launched at the gore tip into the weaving section. Integrating Eq. (2) yields the distance S_R that the on-ramp vehicle traveled

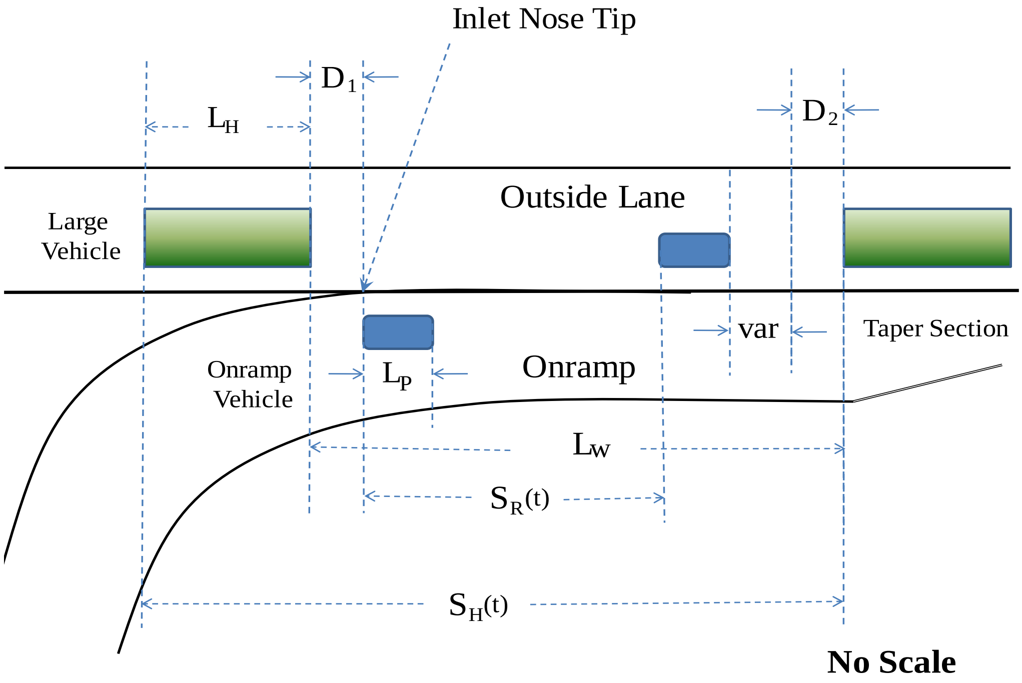

Fig. 1. Schematic Plot for a Difficult Merging Scenario.

after the driver has decided to decelerate.

$$S_R(t) = V_R t \aleph(\delta - t) + \frac{1}{\beta^2}\left[V_R\delta\beta^2 + \alpha\beta(t-\delta) + (\alpha - \beta V_R)\left(e^{-\beta(t-\delta)} - 1\right)\right]\aleph(t-\delta) \quad (3)$$

The traveled distance for constant deceleration can be derived from Eq. (3) by adjusting parameter β to zero as a special case, in which a polynomial expression for the distance $S_R(t)$ can be easily derived via a Taylor series expansion technique.

The distance S_H that the outside lane vehicle traveled with a constant speed v_H over a given time duration t is

$$S_H(t) = v_H t \quad (4)$$

The constant speed assumption is very likely valid for most cases unless congestion takes place. When the merging behind the adjacent vehicle on the outside lane turns out successful, this process should be completed before the onramp vehicle gets into the beginning of the tapering section, implying that

$$L_M - S_R(L_M/v_H) \geqq L_H + L_P + D, \quad (5)$$

$$L_M = L_H + L_w \;, \mathrm{D} = D_1 + D_2 \quad (6)$$

where the length parameters L_w, L_H, L_p, and D, represent respectively the weaving length, the length of the outside lane vehicle, and the length of the onramp vehicle. The adjustable parameter 'D', representing the summation for the minimal distance between the onramp and the adjacent mainline vehicle, varies with the merging situations.

Speed Dependent Onramp Deceleration

Assuming the heavy vehicle moving at a constant speed v_H, Eq. (5) can be explicitly reduced to

$$\frac{1}{\beta^2}\left\{\alpha\beta(\tau-\delta) + (\alpha - \beta V_R)\left[e^{-\beta(\tau-\delta)} - 1\right]\right\} + L_P + L_H + D + V_R\delta - \tau v_H \leq 0 \quad (7)$$

where duration $\tau = L_w/v_H$ is the time which takes the highway vehicle traverses through the weaving section with full lane width.

Eq. (7) in general has one positive and one negative solution, and the unphysical negative solution will be discarded. The exact positive solution for Eq. (7) can be numerically determined by initiating the positive trial solution $\hat{\tau}_0 = -1/\beta$ and then iterating Eq. (8) to find the solution with arbitrary high accuracy.

$$\hat{\tau}_{n+1} = -\frac{1}{\beta} ln\left\{1 - \frac{\beta}{\alpha_1}\left[\alpha_2\hat{\tau}_n + \beta(L_P + L_H - \Delta\delta + D)\right]\right\} = -\frac{1}{\beta} ln\{1-\epsilon\} \quad (8)$$

where parameters $\Delta = v_H - V_R$, $\hat{\tau} = \tau - \delta$, $\alpha_1 = \alpha - \beta V_R$, and $\alpha_2 = \alpha - \beta v_H$. If quantity '$\epsilon$' turns out to be negative, Eq. (8) yields no solution in the field of real numbers, implying that the merging cannot be completed at a reasonable time scale because the onramp vehicle is spatially too close to the adjacent outside-lane vehicles in the merging process; in other words, the ramp wouldn't be long enough when quantity 'ϵ' was negative. Physically, this could occur if the onramp driver's judgment of the merging situation deviates so much from that of a normal driver. If quantity 'ϵ' is positive, Eq. (8) will have a positive real physical solution, and the minimal required onramp length will be

$$L_{wn} = -L_H + v_H(\delta + \hat{\tau}_{100}) \tag{9}$$

where quantity $\hat{\tau}_{100}$ is obtained by iterating Eq. (8) 100 times using an excel spread sheet. Practically, one only needs to iterate Eq. (8) few dozen times in order to achieve the intended accuracy. One may consult this iteration technique elsewhere if needed [6].

Constant Onramp Deceleration Case

For a constant deceleration case with parameter β set to zero or a case in which the deceleration is approximated by a constant, we obtain

$$\frac{\alpha_-}{2}\hat{\tau}^2 - \Delta\hat{\tau} + (L_P + L_H + D - \Delta\delta) = 0 \tag{10}$$

The solution for time duration $\hat{\tau}$ in Eq. (10) is given by

$$\varkappa = \left(\Delta - \sqrt{\Delta^2 - 2\alpha_-\Gamma}\right)/\ \alpha_- \tag{11}$$

where parameter 'Γ' for $L_P + L_H + D - \Delta\delta$, and acceleration parameter 'α_-' is equal to

$$\alpha_- = -g(\mu \pm G) - \beta V_R \tag{12}$$

Variables 'g', 'μ', and 'G' represent respectively the gradational acceleration constant, static tire-road frictional coefficient, and the roadway grade. Grade 'G' would be zero for a road at the horizontal level. It is known that gravitational constant 'g' varies slightly with latitude and the static frictional coefficient 'μ' depends on type of tire-road contact. The correct values for 'g', 'μ', and 'G' for a given scenario would be selected based on the location, geometry of the onramp, and the contact of interest. Note that parameter α for static tire-road skid deceleration is represented by $\alpha = g(\mu \pm G)$. Using Eq. (10), the influence of frictional coefficient on the on ramp length is found to be

$$L_{wn} = -L_H + v_H(\delta + \varkappa) \tag{13}$$

For, example, setting the values 0.0, 11.6 m, 22.4 m, 5.2 m, 9.8 m/s^2, 16 m/s, 26 m/s, and 1.25 s for parameters G, D, L_H, L_P, g, v_R, v_H, and δ respectively, we plot the required onramp length for different values of frictional coefficient in Fig. 2 respectively for speed-dependent deceleration case and the case of constant deceleration.

It is physically known that a vehicle will travel less distance to stop when the deceleration is speed-dependent because the deceleration increases with decreasing speed, hence the cross-sign for constant deceleration lays above the solid line which represents the required weaving length for the speed-dependent deceleration case. It is interesting to point out that difference at around 2% is small between the solid line drawn exactly using Eq. (9) and the cross-sign plotted using Eq. (13). Consequently, applying Eq. (13) for suggesting a slightly larger value for the weaving length is acceptable and could be a good engineering practice. Note that the tire-road frictional coefficient for the HFST, usually above 0.60 but around 0.8, is expected to be functioning independent of foreseeable wet or dry conditions on highway curves [7]. Additionally, examining Fig. 2, one may notice that constructing a short 55 m (180 ft) would be sufficient for a passenger vehicle to decelerate to merge behind a mainline vehicle for many cases if a HFST is applied over the onramp weaving section.

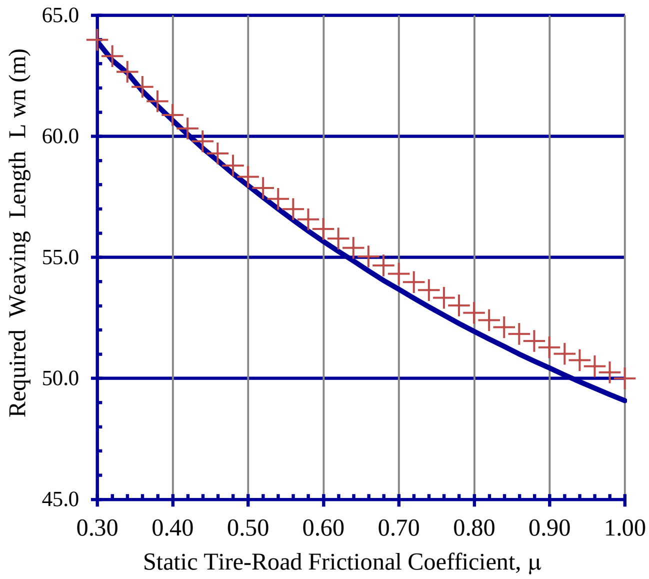

Fig. 2. The Solid Line for the Case of Speed-dependent Deceleration and the Cross Sign for Constant Deceleration Case.

The typical onramp merging length excluding the tapering section varies from one hundred feet or so to a few thousand feet, and this large variation is expected because the ramp design evolves with highway design standard and depends on terrain, available right of way, and traffic demand. It isn't abnormal that some ramps may have been designed and built under design exceptions. Under wet conditions, an average HMA surface may provide a frictional coefficient of 0.3 or much lower if it is partially frosty or icy, indicating that the minimal merging length should be greater than 64 m (220 ft) plus the tapering section length for the scenario discussed in Fig. 2. Ramps with short merging length often become a collision hot spot, where the HFST would become the effective countermeasure for subduing the number of collisions.

Conclusion

The required merging length for an onramp paved with HFST is evaluated based on the exact calculation using Eq. (9) and the approximation using Eq. (13). The exact predictions for various tire-road frictional coefficients using Eq. (9) match very well with the predictions from Eq. (13) for constant onramp deceleration. As a result, using the less complicated Eq. (13) to calculate the required weaving length approximately is justified from a practical standpoint. Additionally, it is found that when applied a HFST to an onramp, one may reduce the required weaving length to 55m (180ft) or less. It isn't our attention to recommend the practitioners to design short ramps with HFST, but for some exceptional cases or situations, an engineer has to design an onramp with very limited right of way, in which the engineer may find both Eq. (9), (13) and/or Fig. 2 applicable. In Fig. 2, the tire-road contact coefficient is chosen to be in the range between 0.3 and 1.0, and it can be made above 1.0 with other durable pavement materials and/or different tire surface materials/patterns/threading. Moreover, the HFST helps reduce collision severity regardless of the outcome of the collision because it dissipates more kinetic energy during and prior to a collision. It is foreseeable that HFST would be widely applicable to many other situations for example at intersections and roundabouts, where severity of certain potential conflict traffic movements may be reduced effectively. Eq. (9) or Eq. (13) when evaluated with the correct parametric values will guide practitioners to find the required onramp merging length upon performing roadway design, traffic safety investigation, traffic engineering studies, or recommending the HFST as a safety countermeasure for reducing onramp traffic accidents. Under some circumstances, it might be foreseeable that the high deceleration on the weaving section could potentially lead to more rear-end but very likely property-damage-only collisions on the onramp. HFST should be paved over at least part of the onramp if substantial numbers of rear-end collision took place on the existing onramp in the past 3 or 5 years or If more rear-end collisions are anticipated for an onramp with relatively high daily traffic volume.

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