AUTOMOBILE BRAKING ON VERY STEEP DOWNGRADES

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CARSP Conference

Victoria, BC. 10-13 June 2018

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SYNECTICS

AIM - PROBLEM

How do you estimate a vehicle's speed at the start of locked wheel braking on a steep down grade from tire marks?

A steep down grade exceeds 10%.

Other steep hills:

- **Beginner's ski hill less than 25%,**
- **Intermediate ski hill, 25 to 45%.**

Highway design usually recommends 8% for major routes, some routes in BC are 10%.

Our experimental data ranges from 0 to 28% grades.

EQUATION
TO ESTIMATE SPEED AT START OF BRAKING

The usual equation to estimate the speed at the start of a vehicle stop on a grade G is:

$$(v)^2 = 2d(\mu(s) - \frac{G}{100})g$$

v = Vehicle speed at start of skid, km/h

d = Skid marks, m

G = Grade, (sign is + for up hill stop and – for downhill stop), %

μ(s)= Vehicle tire pavement friction on level, no units

g = 9.81 m/s^2.

This equation, rearranged to solve for d; given v, μ(s) and G is used for highway design to set the *policy* for Stopping Sight Distance.

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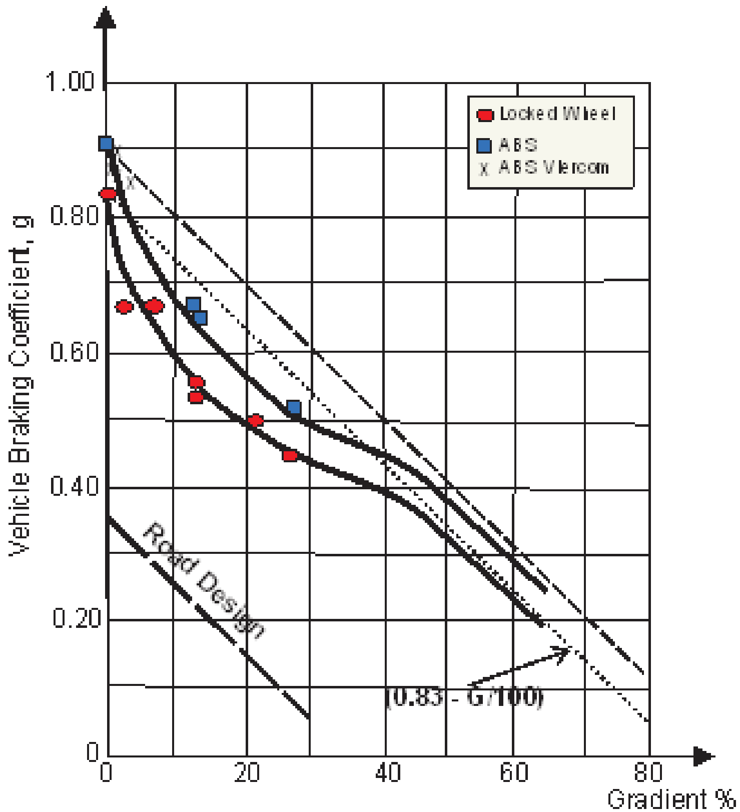
EXPERIMENTAL RESULTS

1993 Corsica, asphalt pavement, at 60km/h (40km/h on 28% grade)

The relationship of the vehicle's braking coefficient is non-linear. It is a complex function.

It does not follow [μ(s)-G/100].

The Road Design, μ(s) is a controlled stop that is less than the vehicle's maximum observed value. It is a *policy*.



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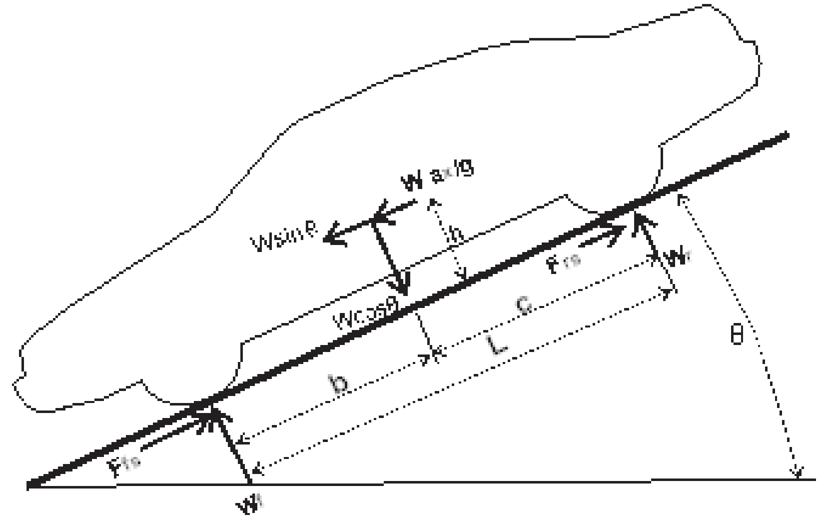
WHY THE DIFFERENCE?

Vehicle weight shift should account for most of the difference since optimal braking is proportional to the load on the tire!



IT DOES NOT WORK, see ABS results.

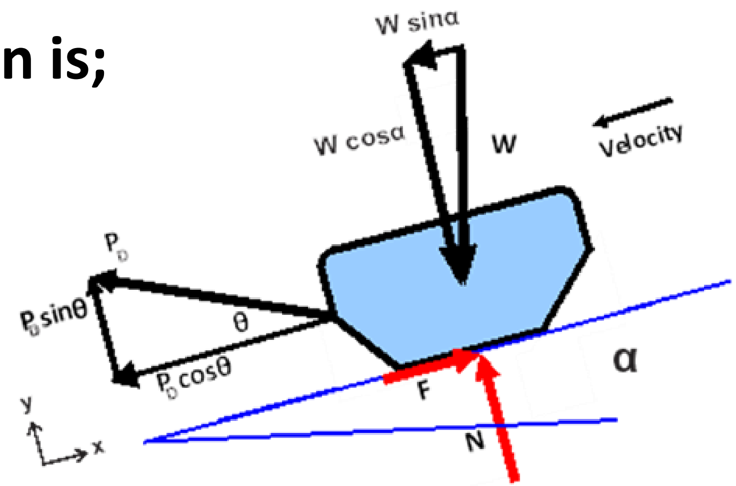
The non-linearity arises due to:

1. **tire-pavement interactions is non-linear by weight and speed,**
2. **ABS braking is set by the manufacture’s design policy, and**
3. **there are probably other factors that need to be measured.**

MEASURING THE COEFFICIENT OF FRICTION

Definition of the coefficient of friction is;

$$\mu(down) = \frac{F}{N} = \frac{Pd\ cos\theta + W\ sin\alpha}{W \cos\alpha\ - Pd\ sin\theta}$$



μ(s) is a tire-pavement property, independent of vehicle and grade.

The mean value of μ(s) for lightly used asphalt is 0.878, and the standard deviation is 0.029. (Used Brakerbox drag sled.)

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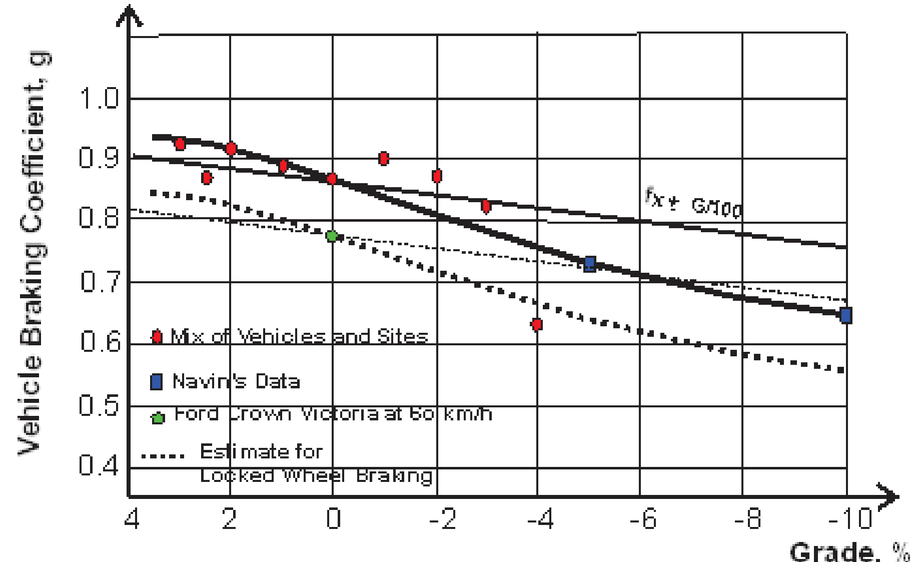
ABS BRAKING ON GRADE

a Selection of Vehicles, Speed about 60 km/h



Solid line is ABS, note the dispersion of results. This is a policy braking system.

Dashed line is Navin's locked-wheel data. It has a tire-pavement limit.

The [µ(s)-G/100] fits the ABS up-grade data quite well, therefore, the locked-wheel data is probably similar.

POLICY BRAKING EXAMPLE ?

Example of ABS Braking Policy?

Consumers Report's **emergency braking test of a Tesla Model 3 from 96 km/h gave a stopping distance of 45.7 m, a deceleration of 0.763 g.**

Tesla claims 0.892 g from 112 km/h.

CR **reported FORD F-150's deceleration of 0.800 g.**

Author's estimate; weight and speed is ~ 0.80 g.

Is this an example of a braking policy issue?

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PRECISION OF BRAKING SPEED ESTIMATES

The data from Navin's down-hill experiments allowed a calculated comparison between speed estimates for the observed speed of 60 km/h (40 km/h at 28% down-grade). The results were as follows.

1. **At down-grades greater than 10% ,**
   the average speed was over estimated by about 10%.

2. **For down-grades less than 10%, the speed error was still high, but reduced towards zero as you approached a level pavement.**

3. **There was no up-grade data.**

CONCLUSIONS

1. **There is no consistent theory for the emergency braking of automobiles on a dry down-grade pavement.**
2. **Equations to predict the speed at the start of skid are based on empirical evidence.**
3. $(v)^2 = 2d(\mu(s) - \frac{G}{100})g$ **is acceptable for Grades +/- 5%.**
4. **More precise equations must account for:**
    1. **vehicle weight,**
    2. **vehicle speed,**
    3. **tire properties,**
    4. **pavement surface properties,**
    5. **road grade, and**
    6. **ABS or locked-wheel braking.**

THANK YOU

Thanks to the reviewers for their encouraging comments.

A very special thanks to *Dennis Payne*, formally of the Florida Highway Patrol who, back in about 1983, first raised this question.

Recently Sgt. *Joseph Weadon* of the Major Crash Investigation Unit, Missouri Highway Patrol, raised the question of emergency braking on steep down grades. This prompted more analysis.

Thank you all for attending this presentation!