SHORT PAPER PCB 9-2006

BRAKE SYSTEM ANALYSIS IN PRE-CRASH ACCIDENT RECONSTRUCTION

ENGINEERING EQUATIONS, INPUT DATA AND MARC 1 APPLICATIONS

By:

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PURPOSE OF PCB SHORT PAPERS

To provide the accident reconstruction practitioner with a concise discussion of the engineering equations and limiting factors involved, evaluation of critical input data, and the analysis of actual cases by use of the MARC 1 computer software.

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Throughout the Short Papers we will extensively reference the 5th Edition of "Motor Vehicle Accident Reconstructions and Cause Analysis" by Rudolf Limpert, the "Accident Reconstruction Catalog" (ARC) CD, as well as the MARC 1 software.

BRAKE SYSTEM ANALYSIS IN PRE-CRASH ACCIDENT RECONSTRUCTION

1.0 Introduction

Depending upon the actual case involved, the accident reconstructionist must be able to answer the following questions with respect a motor vehicle's pre-crash safety or accident avoidance potential:

a. What is the pre-crash deceleration for a vehicle with properly maintained brakes, that is, the manufacturer's brake design level?
b. What is the pre-crash deceleration for a vehicle with improperly maintained brakes?
c. Could the crash have been avoided or its injuries mitigated with properly maintained brakes?
d. What environmental factors such as moisture may have affected the braking effectiveness of the vehicle?
e. What is the maximum no-crash speed with properly maintained brakes?
f. For a motorcycle, what is the deceleration with the rear brake locked, and the maximum deceleration when the front brake is modulated near lockup (ABS)?

Although many of the basic concepts apply to motor vehicles in general, in this paper we will only discuss vehicles equipped with hydraulic brakes. We further assume that the impact speeds are known from standard collision reconstruction.

Throughout the paper we will make reference to two publications and the MARC 1 accident reconstruction software:

Motor Vehicle Accident Reconstruction and Cause Analysis by Rudy Limpert, 5th edition, 1999, published by Matthew Bender (The Text), and

Brake Design and Safety by Rudy Limpert, 2nd edition, 1999, published by SAE International (The Brake Text).

More information and ordering details for both books and MARC 1 can be obtained by visiting our website at www.pcbrakeinc.com

2.0 DESIGN BRAKING EFFECTIVENESS

In Chapters 5 and 7 of the Brake Text all essential engineering equations are discussed that allow the calculation of vehicle deceleration as a function of the basic vehicle parameters such as center-of-gravity height, wheelbase and axle loads (Chapter 7), as well as the actual brake system hardware installed by the manufacturer (Chapter 5).

2.1. BRAKE LOCKUP OR ABS ACTUATION

For straight-line level-road braking, the brakes of an axle lock up when the brake torque exceeds the road torque. Road torque is calculated from the product of dynamic axle load and tire-road friction coefficient, while the actual brake torque is calculated from brake hardware data and brake line pressure and/or brake pedal force.

2.2. OPTIMUM BRAKING FORCES AND LINES OF ONSTANT FRICTION

For a given vehicle and loading configuration the axle loads and center-of-gravity height are known, or can be measured. The relative C.G height is the ratio of actual C.G. height divided by wheelbase. For passenger cars the ratio does not vary greatly, ranging between 0.22 and 0.24. The normalized, that is, braking forces per unit vehicle weight, are shown in Equations 7-8a and 7-8b of the Brake Text.

For the subject SUV the data are: Weight 5150 lb, rear axle load 3006 lb, wheelbase 8.8 ft, and center-of-gravity height 27 inches.

The calculated optimum normalized braking forces, lines of constant deceleration, and lines of constant friction coefficient for a midsize SUV are shown in PCB 9-2006, RUN1 (Figure 1). The diagram lines are only a function of the basic vehicle dimensions and weight characteristics, that is, weight distribution front to rear, wheelbase, and center-of-gravity height. It is the braking "DNA" of the vehicle for the loading condition specified and is not influenced by the brake system hardware installed by the manufacturer. Brake engineers try to match the braking forces generated by the brake system to the optimum forces.

The curved green line is the optimum braking forces line. Any point on the optimum line represent optimum straight-line braking, that is, the deceleration equals the tire-road friction coefficient, as well as both the front and rear axle brakes lockup, or have their ABS system actuate, at the same instant.

The lines running under an angle of 45 degrees are lines of constant deceleration, measured in g-units. For example, the optimum point of 0.8 identifies the 0.8g constant deceleration line. Any where on this line the deceleration is 0.8g, including on the y-axis (FxF Normalized) where all braking is done by the front brakes (rear brakes failed), or on the x-axis (FxR Normalized), where all braking is done by the rear brakes (front brakes failed).

The lines sloping down to the left are lines of constant front friction coefficient. For example, locating the 0.8 optimum point (a = f = 0.8) identifies the line on which the coefficient of friction is f = 0.8 for the front tires. Any where on this line the front tire coefficient of friction is $f_{cF} = 0.8$. For example, if the rear brakes had failed, and the front brakes were locked on a roadway having a tire road-friction coefficient of 0.8, the maximum deceleration would be approximately $a_F = 0.42g$, obtained from the diagram where the 0.8 constant front friction coefficient line crosses the FxF Normalized axis.

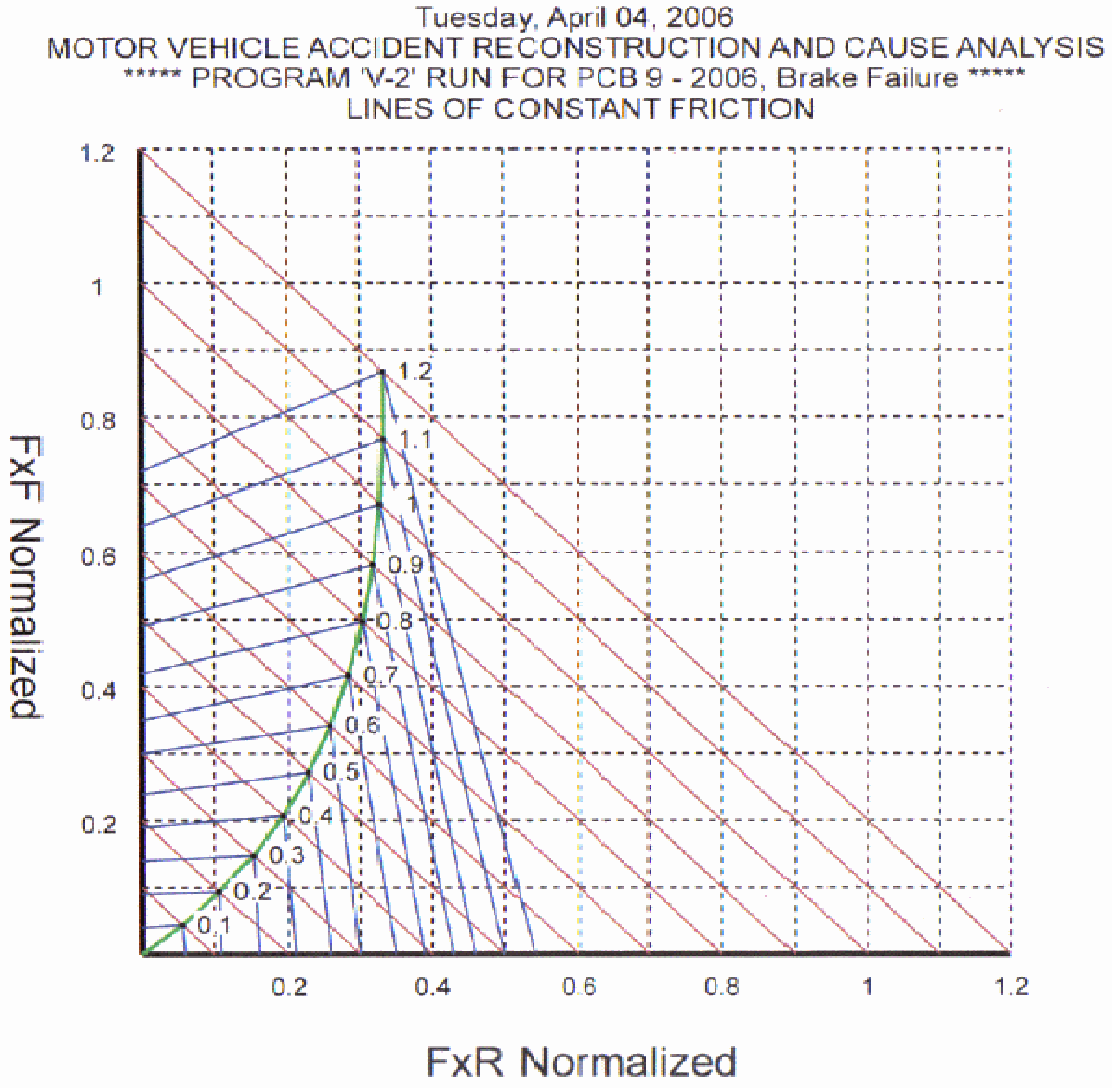


Figure 1. Optimum Braking Forces Diagram

The lines located to the right of the optimum line and sloping steeply to the top are the lines of constant rear friction coefficient. The optimum point 0.8 identifies the constant rear friction coefficient $f_{cR} = 0.8$. Any where on this line the rear tire coefficient of friction is 0.8. If the front brakes had completely failed, the maximum deceleration the subject SUV can achieve with the rear brakes locked is approximately $a_R = 0.39g$, obtained from the interception of $f_{cR} = 0.8$ and the x-axis (FxR Normalized).

2.3. ACTUAL BRAKING EFFECTIVENESS

The braking effectiveness a vehicle can achieve on a roadway with a given tire-road friction coefficient is a direct function of the brake hardware installed by the manufacturer, and/or the mechanical condition as reflected by its maintenance.

Braking effectiveness generally expresses the relationship between pedal force and brake torque generated on all four wheels, and hence, vehicle deceleration. Maximum wheels-unlocked deceleration expresses the quality of a brake system design in relationship to the deceleration that can be achieved at the moment the brakes of one axle lock up.

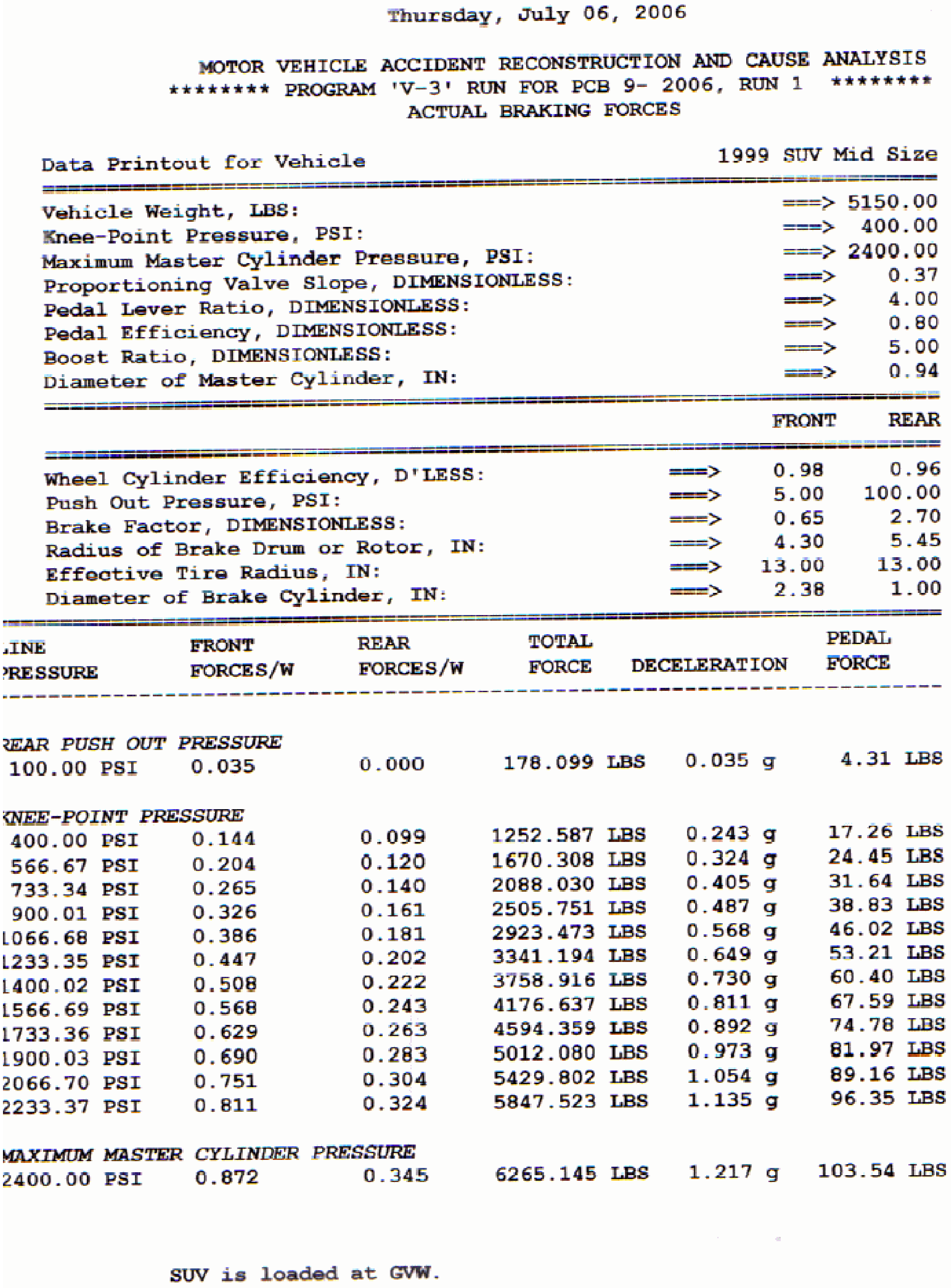
All engineering relationships are discussed in Chapter 5 and 7 of the Brake Text.
The actual braking forces of the subject SUV are sown in the MARC V-3, ACTUAL BRAKINF FORCES printout (Figure 2). Generally, the input data can be obtained from detailed vehicle inspection including brake dimensions, wheel cylinder sizes, lining material edge codes (friction coefficient), and repair manuals. The probable rear brake factor for drum b rakes can be calculated from Chapter 2 equations of the Brake Text. The subject SUV used leading-trailing shoe rear drum brakes with a brake factor of 2.7 for an edge code FE ($f_{lining} = 0.37$) as calculated from basic brake dimensions and illustrated in Figure 3.

Inspection of the actual braking forces table (Figure 2) shows that the loaded SUV yields a deceleration of approximately 0.81g for a pedal force of 68 lb.

MARC 1 V-3 can be used to study the effects of certain brake failures on braking effectiveness, such as booster failure or hydraulic circuit failure. For example, if the booster failed, that is, B = 1 (instead of 5), the pedal force required for a 0.49g stop would require approximately 201 lb of pedal force. Similarly, if the front brakes would experience a complete hydraulic failure (the subject SUV has a front-to-rear hydraulic split brake system), with $BF_F = 0$ (instead of 0.65) a deceleration of 0.24g requires a pedal force of 69 lb, assuming the vacuum booster has not yet saturated.

3.0. BRAKING FORCES DIAGRAM

In the braking forces diagram the actual braking forces are compared with the optimum braking forces. The braking forces diagram is used to accurately determine the probable vehicle deceleration when brakes lock.



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             MOTOR VEHICLE ACCIDENT RECONSTRUCTION AND CAUSE ANALYSIS
          ******** PROGRAM 'V-3' RUN FOR PCB 9- 2006, RUN 1   ********
                          ACTUAL BRAKING FORCES

  Data Printout for Vehicle                               1999 SUV Mid Size
  ==========================================================================
  Vehicle Weight, LBS:                                         ===> 5150.00
  Knee-Point Pressure, PSI:                                    ===>  400.00
  Maximum Master Cylinder Pressure, PSI:                       ===> 2400.00
  Proportioning Valve Slope, DIMENSIONLESS:                    ===>    0.37
  Pedal Lever Ratio, DIMENSIONLESS:                            ===>    4.00
  Pedal Efficiency, DIMENSIONLESS:                             ===>    0.80
  Boost Ratio, DIMENSIONLESS:                                  ===>    5.00
  Diameter of Master Cylinder, IN:                             ===>    0.94
  ==========================================================================
                                                          FRONT      REAR
  ==========================================================================
  Wheel Cylinder Efficiency, D'LESS:                 ===>    0.98      0.96
  Push Out Pressure, PSI:                            ===>    5.00    100.00
  Brake Factor, DIMENSIONLESS:                       ===>    0.65      2.70
  Radius of Brake Drum or Rotor, IN:                 ===>    4.30      5.45
  Effective Tire Radius, IN:                         ===>   13.00     13.00
  Diameter of Brake Cylinder, IN:                    ===>    2.38      1.00
===========================================================================
LINE           FRONT        REAR         TOTAL                     PEDAL
PRESSURE       FORCES/W     FORCES/W     FORCE      DECELERATION   FORCE
---------------------------------------------------------------------------

REAR PUSH OUT PRESSURE
 100.00 PSI    0.035        0.000      178.099 LBS    0.035 g      4.31 LBS

KNEE-POINT PRESSURE
 400.00 PSI    0.144        0.099     1252.587 LBS    0.243 g     17.26 LBS
 566.67 PSI    0.204        0.120     1670.308 LBS    0.324 g     24.45 LBS
 733.34 PSI    0.265        0.140     2088.030 LBS    0.405 g     31.64 LBS
 900.01 PSI    0.326        0.161     2505.751 LBS    0.487 g     38.83 LBS
1066.68 PSI    0.386        0.181     2923.473 LBS    0.568 g     46.02 LBS
1233.35 PSI    0.447        0.202     3341.194 LBS    0.649 g     53.21 LBS
1400.02 PSI    0.508        0.222     3758.916 LBS    0.730 g     60.40 LBS
1566.69 PSI    0.568        0.243     4176.637 LBS    0.811 g     67.59 LBS
1733.36 PSI    0.629        0.263     4594.359 LBS    0.892 g     74.78 LBS
1900.03 PSI    0.690        0.283     5012.080 LBS    0.973 g     81.97 LBS
2066.70 PSI    0.751        0.304     5429.802 LBS    1.054 g     89.16 LBS
2233.37 PSI    0.811        0.324     5847.523 LBS    1.135 g     96.35 LBS

MAXIMUM MASTER CYLINDER PRESSURE
2400.00 PSI    0.872        0.345     6265.145 LBS    1.217 g    103.54 LBS


               SUV is loaded at GVW.
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Figure 2. Actual Braking Forces

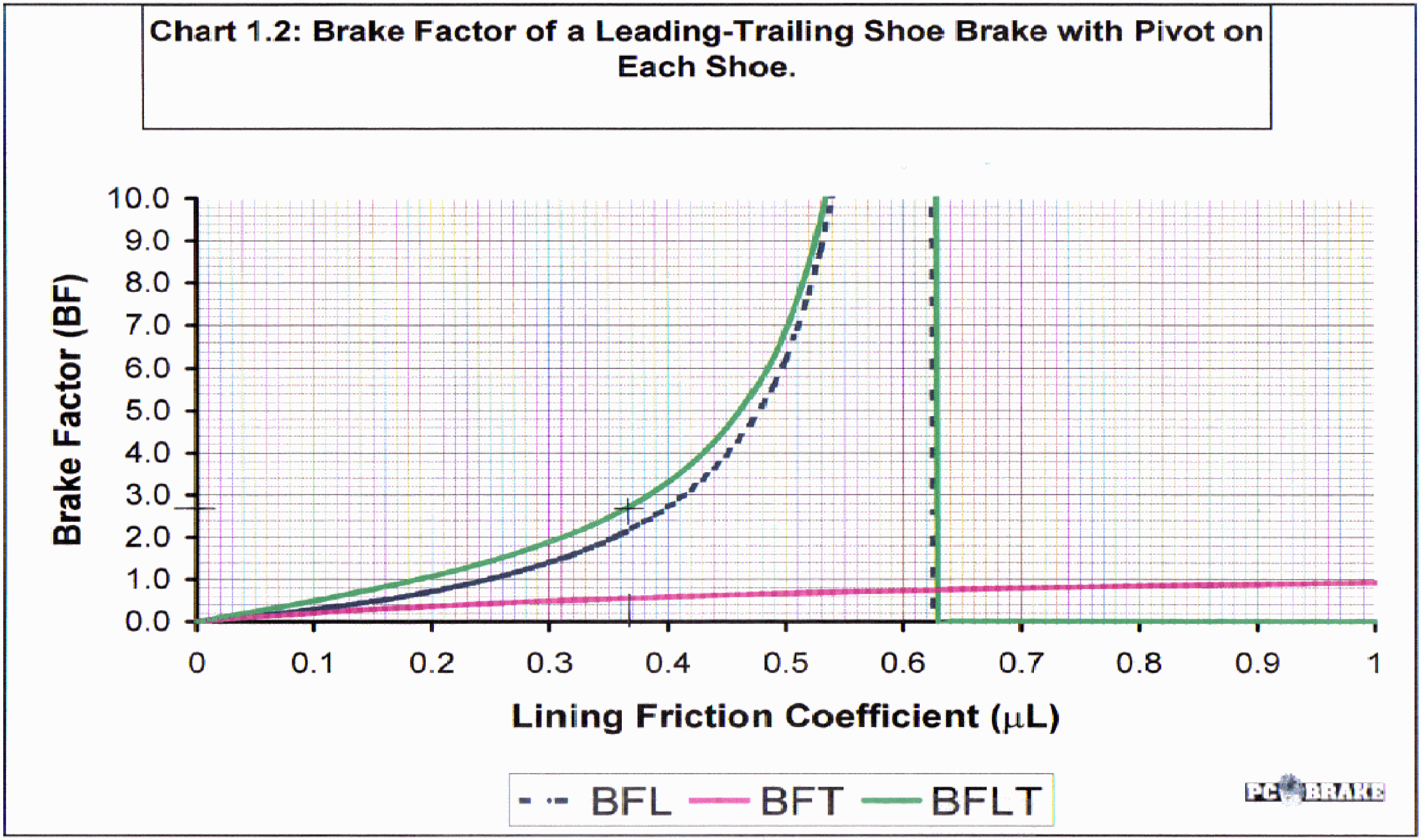


Figure 3. SUV Rear Drum Brake

The braking forces diagram for the subject SUV is shown in Figure 4. A blowup of the same diagram is shown in Figure 5. The red line consisting of three straight segments is the actual braking forces line. Beginning at the origin, the system produces only front braking forces due to the push-out pressure of the rear brakes. At a deceleration of approximately 0.035g (see also print-out) the rear brakes begin producing braking forces, causing the actual braking forces to rise under an angle until they reach the braking forces corresponding to the knee point brake line pressure at a deceleration of approximately 0.24g. For greater braking forces the actual braking forces line slope up, intersecting the optimum line at approximately 1.17g. As long as the red actual braking forces line is to the left of the optimum line, front brakes will lock up before the rear brake lock. The vehicle is directionally stabile, since front brakes lock before rear brakes for all reasonably foreseeable decelerations.

Inspection of Figure 5 reveals that for a tire-road friction coefficient of 0.8 the front brakes will lockup at a deceleration of approximately 0.68g. If pre-impact front skid marks were located at the accident scene, the reconstructionist can safely use a “proven” deceleration of 0.68g. The reason for the relatively low deceleration at the moment the front brakes lock is caused by a significant static rear axle load, and hence, low front axle load. If at some point later the rear brakes also locked up, that is, the driver continued to increase pedal force beyond the point of first tire lockup, the actual braking forces line moves along the line of constant front friction until the final point of rear lockup is achieved at the 0.8 point on the optimum line. Now brakes on both axles are locked and the vehicle deceleration is 0.8g.

If the road surface is not dry, then the braking forces diagram easily yields the appropriate decelerations at front brake lockup. For example, f = 0.6 yields a = 0.48g, f = 0.55 (estimated by drawing constant friction line) a = 0.45g (wet), f = 0.3 a = 0.24g (snow).

3.0. BRAKING EFFECTIVENESS WITH BRAKE FAILURE

The particular SUV involved in the accident experienced a brake failure prior to the crash. The driver stated that the pedal travel was more than normal, and that when he applied the brakes the brakes did not “catch”. The reader is encouraged to study Section 41-11 of the Supplement to the Text for detailed questioning of a driver involved in a brake failure accident.

Brake system repair work including the replacement of a hydraulic valve had been carried out one day before the accident. Inspection of the brake system of the subject SUV did not reveal any brake fluid leaks. All hydraulic connection were tight, pad and lining thickness data were well within acceptable limits, swept rotor and drum surfaces showed no signs of overheating, front brake calipers allowed free and unobstructed pad apply and return movements, and the brake fluid appeared to be new consistent with the repair work.

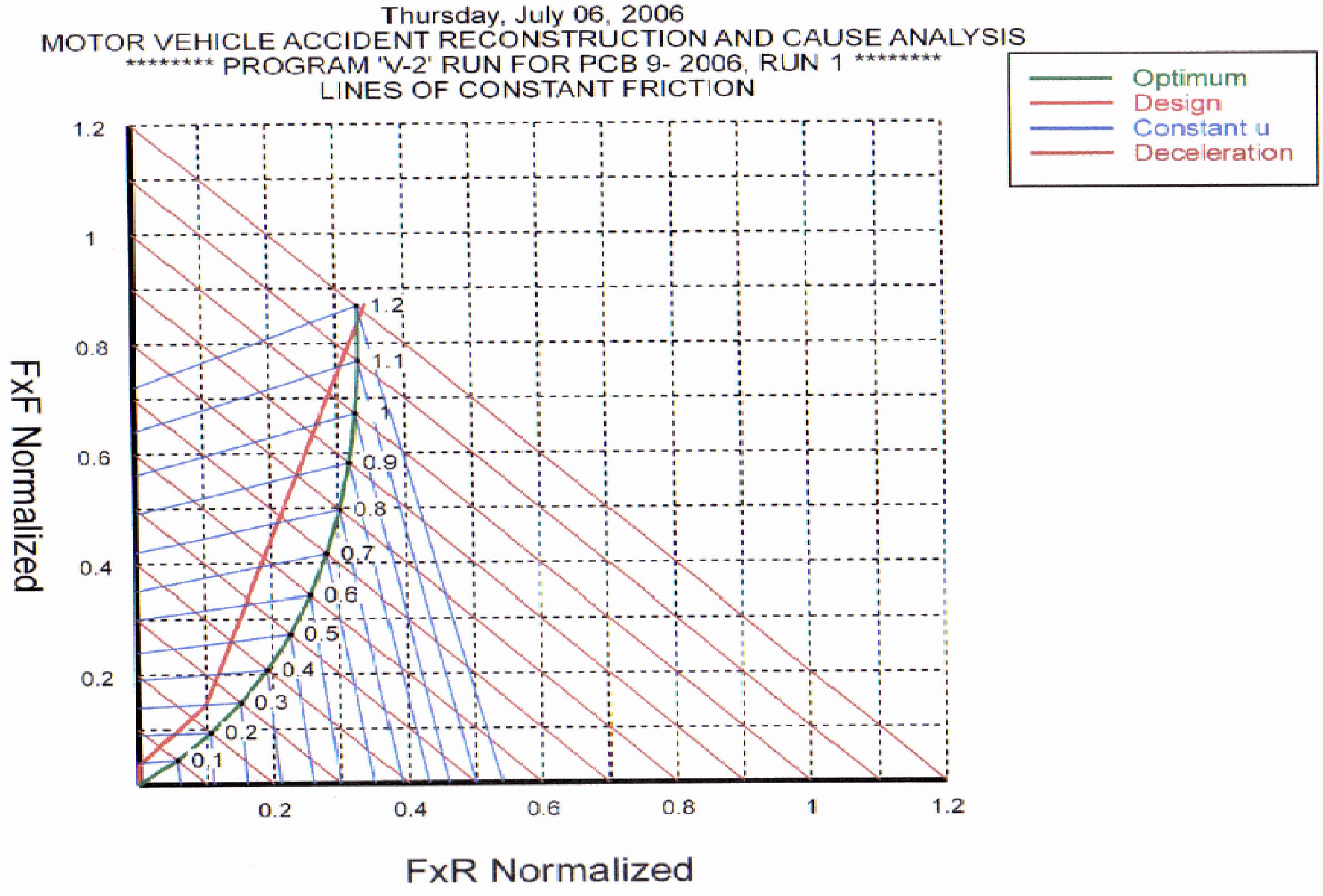


Figure 4. Braking Forces Diagram

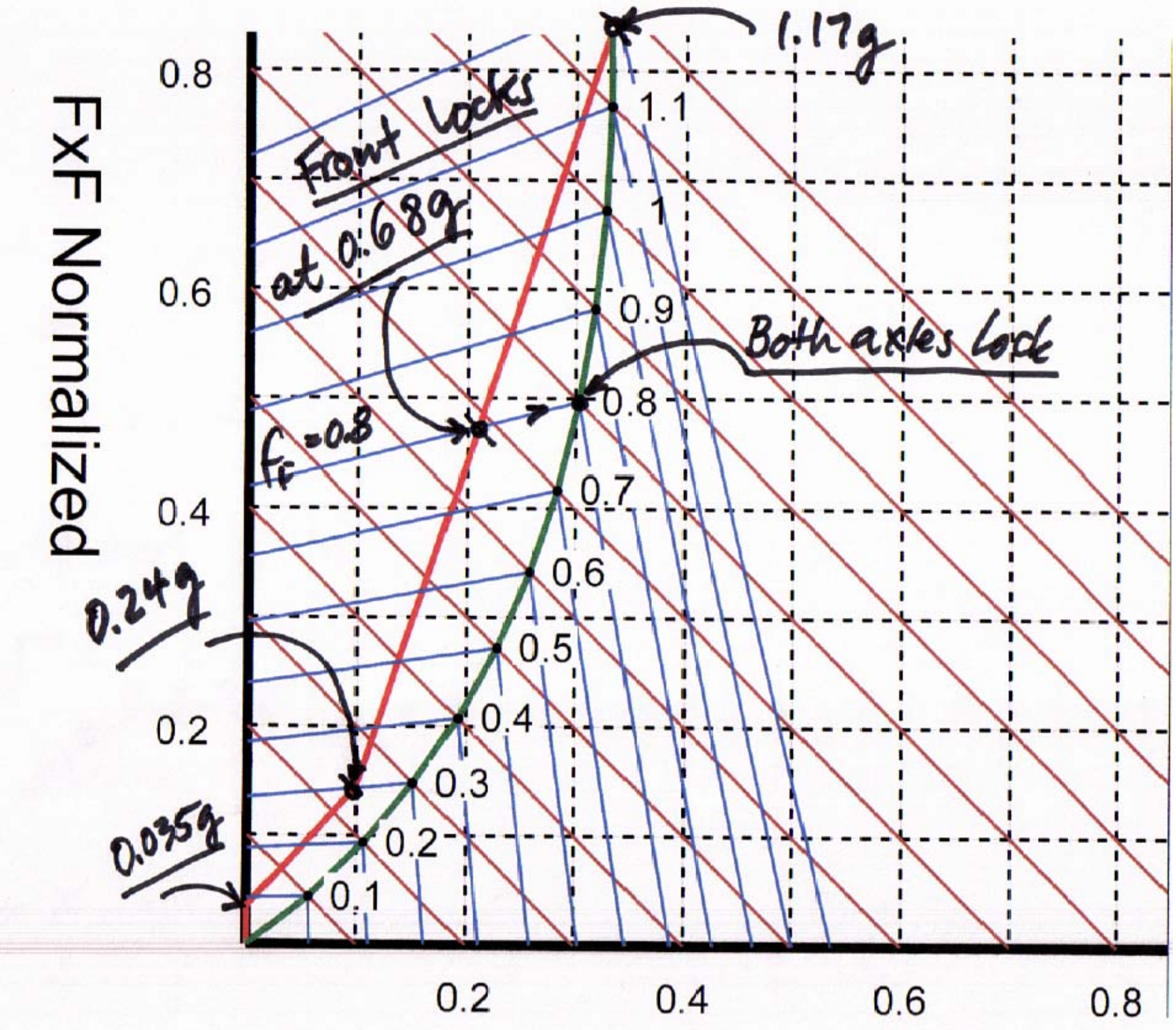


Figure 5. Blowup of Figure 4

During the lateral run-out measurements of the left front brake an axial bearing play of 0.050 in. was measured. Normal axial bearing play is zero. Since the setscrews, holding the bearing nut in place, were properly fastened, it was concluded that at some prior repair the bearing was not adjusted properly. It therefore became the expert's task to determine how much braking, if any, the front brakes produced, and if with increased brake pedal force the rear brakes would lock, and if so, at what deceleration.

The mechanism in the partial brake failure involves the knock-back of the left front pads and piston during normal driving since the rotor is not held firmly in place by the bearing. The result is excessive left front wheel cylinder piston travel required to bring the brake pads in contact with the rotor prior to any brake line pressure production. A detailed discussion of brake fluid volume requirements is presented in Section 5.4.3 of the Brake Text.

The master cylinder of the subject SUV has the following dimensions and volumes: Diameter 23.81 mm, front piston travel 19 mm, rear piston travel 13 mm. The useable brake fluid volume available from the front circuit portion of the master cylinder is 7.3cm^3 or 0.445 in^3.

The volume requirements of the brake system fall into tow categories, namely those components using brake fluid prior to any brake line pressure production, and those involved in pressure production.

Zero Pressure Volumes:

Zero pressure volume of left front caliper:

$$V_{CLF} = (A_{wcF})(S_{padLF}) = (4.43)(0.050 + 0.002 + 0.013) = 0.288 \text{ in}^3$$

The input data are as follows:

4.43 in^2 is the cross sectional area of the front wheel cylinder piston, 0.050 in lateral bearing play, 0.002 in. rotor lateral run-out, 0.013 in. piston travel due to normal air inclusion associated with a caliper of this size.

Zero pressure volume of right front caliper:

$$V_{CRF} = (4.43)(0.002 + 0.013) = 0.0665 \text{ in}^3$$

The total zero pressure fluid volume required is 0.3545 in^3. The fluid volume available for brake line pressure production on the front brakes is 0.445 – 0.3545 = 0.0905 in^3.

Pressure Volumes:

Metallic Brake Line with volume loss coefficient (Equ. 5-26 of Brake Text) and 100 in. tube length:

$$V_{BL} = (0.0064)(10^{-6})(100)\ p_l = (0.64)(10^{-6})\ p_l\ ,\ in^3$$

Brake Hose with volume loss coefficient (Equ. 5- 28 0f Brake Text) and 40 in. hose length:

$$V_{BH} = (0.47)(10^{-6})(40) = (18.8)(10^{-6})\ p_l\ ,\ in^3$$

Master Cylinder volume loss (table on page 226 of Brake Text):

$$V_{mc} = (8)(10^{-6})\ p_{l\ ,}\ in^3$$

Elastic Caliper Deformation (Equ. 5-31 of Brake Text):

$$V_{calF} = (2)(52x2.375 – 69)(10^{-6})\ p_l = (109)(10^{-6})\ p_l\ ,\ in^3$$

Pad Compression (Equ. 5-33 of Brake Text):

$$V_{pF} = (4)(4.43)(5)(10^{-6})\ p_l = (88.6)(10^{-6})\ p_l\ ,\ in^3$$

Brake Fluid Compression (Equ. 5-39):

$$V_{BfF} = (10)(5)(10^{-6})\ p_l = (50)(10^{-6})\ p_l\ ,\ in^3$$

An active volume of 10 in^3 and compressibility factor of 5 1/psi (Figure 5-23) were assumed for brake fluid compressibility calculations.

Proportioning Valve (measured data may show 0.2 in^3at 1200 psi brake line pressure)

$$V_{prop} = (25)(10^{-6})\ p_l\ ,\ in^3$$

The maximum brake line pressure that can be produced by the front brake circuit is limited by the volume available for from the master cylinder, namely 0.0905 in^3, and the front brake system volume requirements as pressure increases.
The front circuit brake line pressure is:

$$p_{lF,max} = (0.0905)/((300.04)(10^{-6}) = 301.6\ psi$$

The failure analysis shows that the front circuit master cylinder piston will bottom out at a brake line pressure of approximately 302 psi.

We must now calculate the deceleration of the subject SUV when the brake line pressure has reached 302 psi. Chapter 5 equations of the Brake Text can be used, or MARC1 V-3 where the knee-point pressure is changed temporarily to 302 psi. This can be done since the actual knee point of the subject SUV is greater than the front brake limit pressure. Using MARC 1 yields a deceleration of 0.175g with corresponding normalized front and rear braking forces of 0.108 and 0.067, respectively. If the front limiting brake line pressure had been greater than the knee-point pressure, the maximum master cylinder pressure would have been used as front brake limiting pressure.

The operating point of the braking system with the front system limiting the normalized front braking force F_{xF}/W to 0.108 is shown in Figure 6. Any further increase in braking force due to increased rear braking is shown by the horizontal line. The interception of the rear constant friction line of 0.8 with the horizontal (rear) braking forces operating line indicates a maximum deceleration of approximately 0.48g as the rear brakes lock (or the rear ABS begins to actuate). Even if the driver were to apply greater pedal forces, the deceleration is limited to 0.48g. If the roadway had been wet with a friction coefficient of only 0.5, the rear brakes would lock at approximately 0.36g. The corresponding non-failed deceleration with the front brakes locking would have been approximately 0.68g.

In the actual case, the excessive play of the left front bearing apparently disabled the ABS system, and in connection with the partial failure of the front brakes, caused the rear brake to lock at a deceleration of approximately 0.48g resulting loss of directional stability and rollover of the SUV.

4.0 BRAKING EFFECTIVENESS AFFECTED BY MOISTURE

In the past larger passenger cars and pickup trucks frequently used rear duo-servo drum brakes. As discussed in Chapter 2 of the Brake Text, duo-servo brakes generally exhibit large brake factors with high sensitivity to lining friction coefficient changes. Exposure to moisture may increase the rear drum brake factor by 30 to 35% due to a relatively small increase of the brake lining coefficient of friction of only 10%. The braking forces diagram is well suited to efficiently analyze potential premature rear brake and loss of directional stability due an increase in actual rear braking forces. See Figure 24-9 of the Text.

5.0 BRAKING FORCES DIAGRAM FOR MOTOR CYCLE

In a particular case, a heavy motorcycle laid down a pre-crash rear tire skid mark of 87 ft, followed by 47 ft of additional front brake lockup, at which point the motorcycle capsized and slid on its side for 25 feet before impacting a car turning left into the pass of the oncoming motorcycle. The roadway was dry with an estimated tire-road friction coefficient for the motorcycle of 0.9. The impact speed against the right side of the car was estimated from crush damage and motorcycle weight to have been 17 mph.

Since motorcycle brake systems have front and rear brake independent of each other, we only need to develop the diagram showing the optimum and lines of constant friction.

The weight of the motorcycle including operator was 620 lb, the static rear axle load approximately 335 lb, the wheelbase 4.7 ft, the center-of-gravity height 2.3 ft.

The optimum braking forces diagram is shown in Figure 7 obtained from MARC 1 V2.

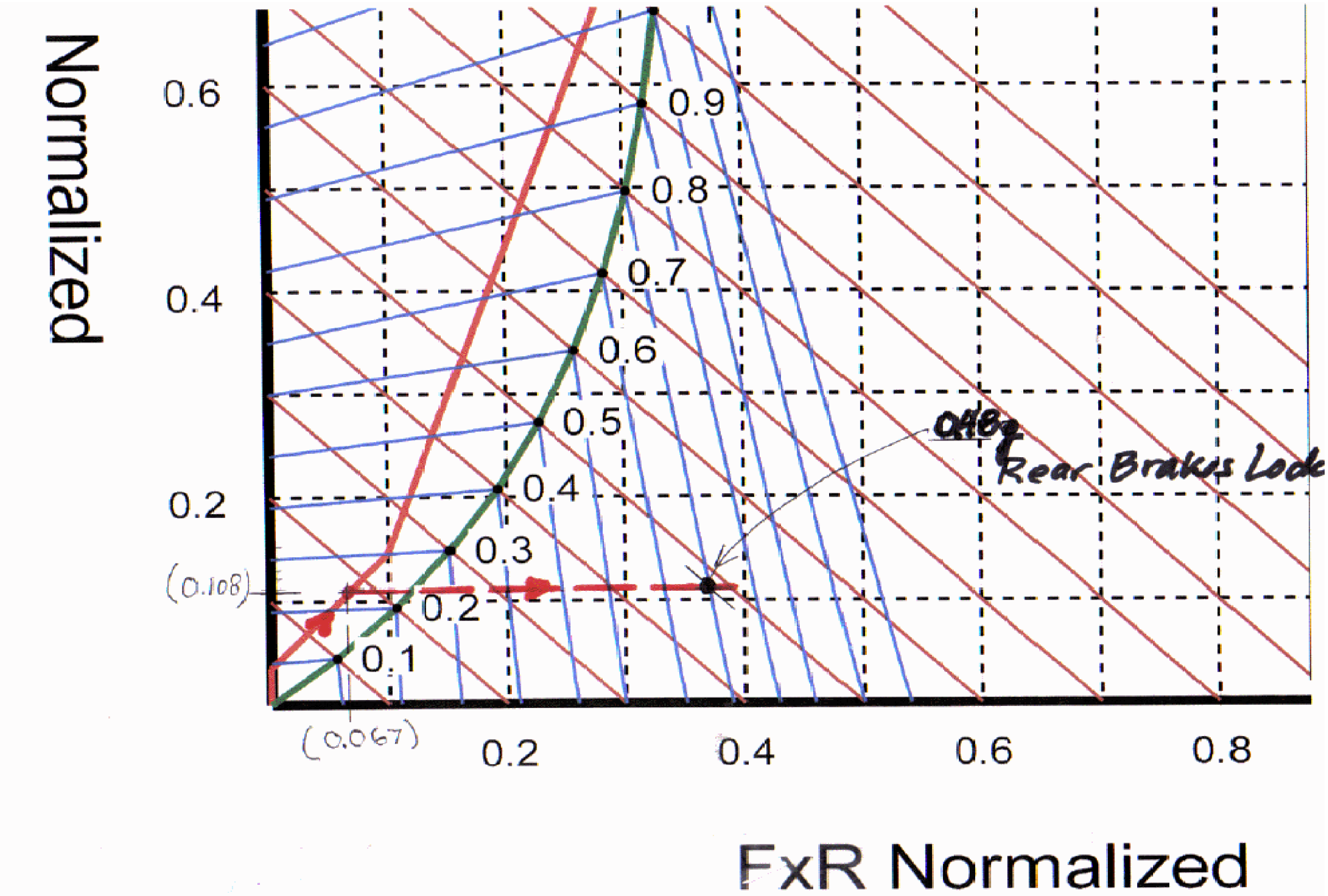
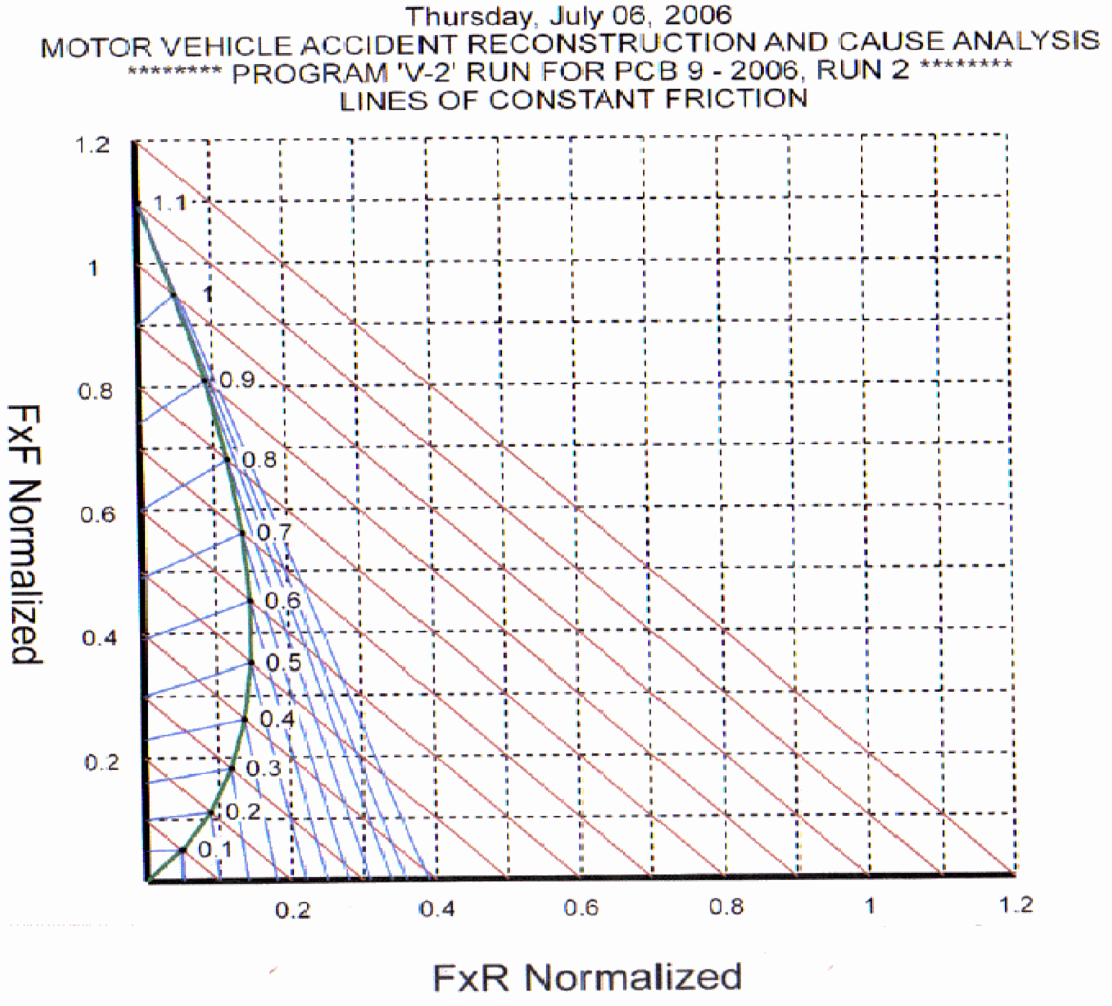


Figure 6. Braking Forces Diagram With Front Brake Failure

Inspection of Figure 7 reveals that the “DNA” of the motorcycle is such that the rear wheel lifts off the ground for a theoretical deceleration of 1.1g, assuming the front brake torque is sufficient and the front tire-road friction coefficient at least 1.1.

The operator first applied the rear brake until lockup. Inspection of Figure 8 (blowup of Figure 7) reveals for no front braking a deceleration of approximately 0.34g for a tire-road friction coefficient of 0.9. As the operator also applied the front brake, the braking forces operating line moves along the line of constant rear friction until it reaches the point of 0.9 on the optimum curve, that is, the point of front brake lockup. At this moment the deceleration of the motorcycle is 0.9g.

For a heavy motorcycle sliding on its side a drag factor of 0.55 is used (Table 36-1 of the Text), resulting in the following pre-crash speeds: 26.5 mph at tip-over, 44.4 mph when front brake locked, and 53.5 mph when rear brake locked (See Section 20-4(f), Combined Speeds, of the Text).



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MOTOR VEHICLE ACCIDENT RECONSTRUCTION AND CAUSE ANALYSIS
********* PROGRAM 'V-2' RUN FOR PCB 9 - 2006, RUN 2 *********
LINES OF CONSTANT FRICTION

Figure 7. Optimum Braking Forces For Motorcycle

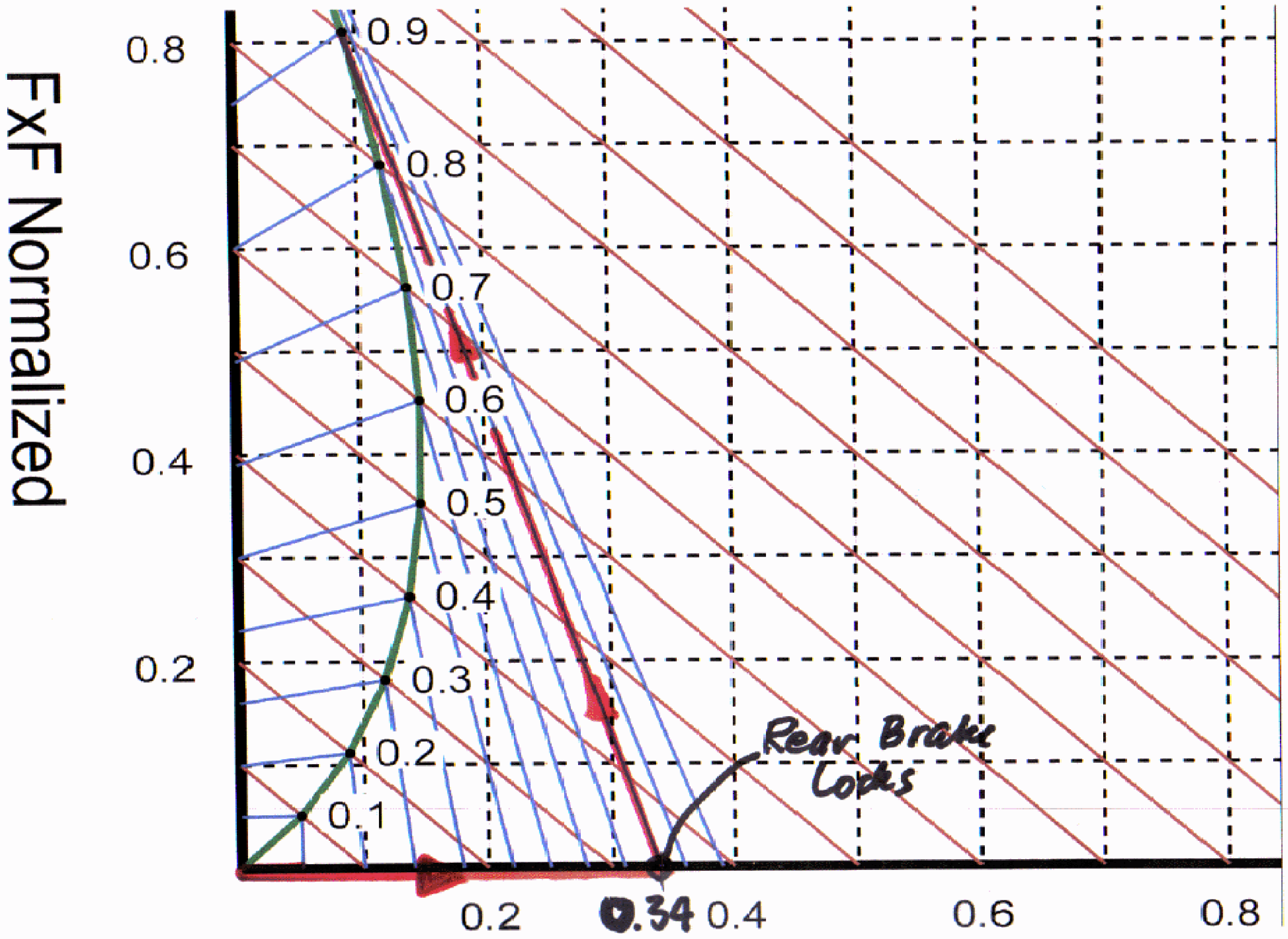

Figure 8. Blowup of Figure 7