ANTILOCK BRAKE SYSTEMS AND RISK OF DIFFERENT TYPES OF CRASHES IN TRAFFIC

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ABSTRACT

While antilock brakes (ABS) have been convincingly demonstrated to enhance test track braking performance, their effect on crash risk in actual driving remains less clear. This paper examines how ABS influences crash risk using mainly two published studies which used police-reported crashes. The published findings are augmented by including new data and additional results. All the work is based on seven General Motors passenger vehicles having ABS as standard equipment for 1992 models but not available for 1991 models. The ratio of crashes under an adverse condition (say, when the pavement is wet) to under a normal condition (say, when the pavement is dry) is compared for ABS and *non*-ABS vehicles. After correcting for such factors as model year effects not linked to ABS, the following associations between ABS and crash risk were found by averaging data from the five states Texas, Missouri, North Carolina, Pennsylvania and Indiana (the errors are one standard error); a (10 ± 3)% relative lower crash risk on wet roads compared to the corresponding comparison on dry roads; a (22 ± 11)% lower risk of a pedestrian crash compared to the risk of a non-pedestrian crash; a (39 ± 16)% increase in rollover crash risk compared to the risk of a non-rollover crash. Data from the same five states were used to examine two-vehicle rear-end collisions. Using the assumption that side-impact crashes estimate exposure, it was found that for wet roads ABS reduces the risk of crashing into a lead vehicle by (32 ± 8)%, but increases the risk of being struck in the rear by (30 ± 14)%. The results from this study and from all available reported studies are summarized in tabular form.

INTRODUCTION

Anti-lock braking systems (ABS) use electronic controls to maintain wheel rotation under hard braking that would otherwise lock a vehicle's wheels. Keeping the wheels rotating increases vehicle stability, especially when tire/roadway friction is reduced or varying, as when the pavement is wet. Prior general understanding of the relationship between improved braking and safety [1, p 282-306], together with earlier specific literature on antilock braking, leads one to anticipate a complex interaction between ABS and safety.

Test track evaluations have convincingly demonstrated the technical advantages of ABS under a wide variety of conditions [2-4]. A study [5] analyzing historical traffic crash data for a non-ABS vehicle fleet predicted that universal ABS in Germany could diminish severe crashes by 10 to 15%. However, when taxi drivers in Munich were randomly assigned vehicles with and without ABS, no overall difference in crash rates between the two groups was observed, although each group experienced different types of crashes [6]. Because the severity of crashes apparently induced by ABS was less than that for the crashes prevented, the study suggests that the ABS system led to a net reduction in harm. An analysis of Swedish insurance data uncovered associations between the rates of occurrence of different types of crashes and ABS [7]. An analysis of Canadian insurance data found a 9% reduction in claim frequency, but a 10% increase in average claim severity [8]. The Highway Loss Data Institute [9] found no change associated with ABS in either the frequency or severity of traffic crashes. A study [10] using police-reported crashes per registered vehicle reports a 6% to 8% reduction in crash risk due to ABS, while another study using fatal crashes [11] finds an increase in risk to occupants of ABS equipped vehicles but a decrease in risk to other road users.

The present paper aims at increasing understanding about the relationship between ABS and traffic safety by summarizing the results of two recent studies [12,13], augmenting these results with additional data and findings, and then comparing the results to other results in the literature.

The first of the two studies [12] examined how ABS affects the relative risk of crashes in general under different roadway, environmental, and other conditions using data on police reported crashes from two states (Texas and Missouri). The second study [13] was confined to two-car crashes, and examined the following two questions: How does ABS affect a vehicle's risk of crashing into a vehicle it is following? How does ABS affect a vehicle's risk of being struck in the rear? This study used data from five states (Texas, Missouri, North Carolina, Pennsylvania and Indiana -- listed in the order of number of relevant crashes).

In the present paper the results of the first study are updated by including data from all five states.

APPROACH

The ratio of the number of crashes under an adverse or unusual condition (say, when the pavement is wet) to the number of crashes under a standard, normal or comparison condition (say, when the pavement is dry) is computed for some specified group of vehicles. This wet to dry crash involvement ratio will be the same for two groups of vehicles whose crash rates are the same under either wet or dry conditions. However, the ratio is different for a group of vehicles possessing a characteristic that influences crash rate more under wet than under dry conditions. Comparing the *wet to dry* ratio for a group of ABS-equipped vehicles to the corresponding ratio for an otherwise identical group of *non-*ABS vehicles measures the influence of ABS on relative crash risk.

The comparison is relative -- a reduction in the *wet to dry* ratio occurs if ABS is associated with a decrease in the number of *wet* crashes or an increase in the number of *dry* crashes; the method cannot identify the extent to which it is changes in the numerator versus changes in the denominator that lead to the observed changes in the ratio. Purely for expository convenience and clarity, we make the temporary simple assumption that the risk under the standard condition (dry in this example) is unaffected by ABS. The results can readily be recalculated based on any assumed change in crash risk in the standard condition due to ABS.

Table 1.
ABS availability in the study vehicles

	Model Year	
	1991	1992
Chevrolet Cavalier	No	Yes
Chevrolet Beretta	No	Yes
Chevrolet Corsica	No	Yes
Chevrolet Lumina APV	No	Yes
Pontiac Sunbird	No	Yes
Pontiac Trans Sport	No	Yes
Oldsmobile Silhouette	No	Yes

DATA

The same seven vehicles used in the Highway Loss Data Institute study [9] (Table 1) provide the data for this study. All are GM passenger vehicles that did not offer ABS in 1991 models, but had ABS as standard equipment in 1992 models. Thus the comparison is between the crash risks of the 1992 model year (MY) vehicles and the 1991 MY versions of these vehicles.

In all the analyses presented here, data for calendar years 1992 and 1993 are combined.

CALCULATIONS

The calculation procedures used are described in terms of the specific example of comparing crashes when the pavement is wet to when the pavement is dry using numerical values from the Texas data. We first estimate the quantity R_1, defined as

$$R_1 = \frac{A_{wet}}{A_{dry}} \div \frac{N_{wet}}{N_{dry}} \qquad (1)$$

where A = Number of crashes by ABS-equipped vehicles, and
N = Number of crashes by *non*-ABS-equipped vehicles,

and the subscripts indicate the pavement condition when the crashes occurred. The Texas data provide the following values:

A_{wet} = 579 N_{wet} = 1219

A_{dry} = 3118 N_{dry} = 4865 .

These values show that 579/(579+3118) = 15.7% of the crashes by ABS-equipped vehicles occurred on wet pavement, compared to 20.0% for the *non*-ABS vehicles. Substituting into eqn 1 gives

$$R_1 = 0.7411 \ . \qquad (2)$$

If the ABS and *non*-ABS vehicles differed in no other characteristics that could affect crash involvement risk, then R_1 would measure directly the influence of ABS. The value R_1 = 1 indicates no effect, R_1 < 1 indicates reduced risk for ABS vehicles on wet roads, and R > 1 indicates increased risk for ABS vehicles (assuming that ABS does not affect crash risk on dry roads). The above values suggest a 25.89% reduction in crash risk on wet roads for the ABS vehicles. However, such an inference is invalid because of the presence of two important biasing effects.

Two biasing, or confounding, interactions

First, a *model year effect.* The ABS-equipped vehicles are all model year 1992, whereas the *non*-ABS vehicles are all model year 1991. Thus, the typical *non*-ABS crash compared to the typical ABS crash involved a vehicle approximately one year older. It is well established that crash rates depend systematically on vehicle age [14].

Second, what might be referred to as a *ramp-up effect.* By the beginning of the period for which crashes are included in the data, namely 1 January 1992, nearly all the 1991 MY vehicles were already registered. Hence, throughout calendar year 1992 they were all exposed to risk. In contrast, by 1 January 1992 few 1992 MY vehicles had been registered. As calendar year 1992 progresses from January to December, the number of 1992 MY vehicles registered steadily increases. As the roadway and weather conditions on which this study focuses change throughout the year, this ramp-up effect could introduce serious bias. For example, if there was much snow in January 1992, this would generate many crashes on snow by the already present 1991 MY vehicles. However, the 1992 MY vehicles not yet registered cannot experience these crashes, thus biasing R_1 downwards, and inviting a false attribution of reduced crashes to ABS rather than the ABS vehicles being not exposed.

Estimate of influence of ABS on relative risk

The model year effect and the ramp-up effect can both be corrected for by computing a second ratio, R_2, defined as

$$R_2 = \frac{92MY_{wet}}{92MY_{dry}} \div \frac{91MY_{wet}}{91MY_{dry}} , \qquad (3)$$

where 92MY = Number of crashes by 1992 model year vehicles,
91MY = Number of crashes by 1991 model year vehicles.

The seven makes in Table 1 are excluded from the computation of R_2. The Texas data provide the following values:

$92MY_{wet}$ = 16,509 $\qquad$ $91MY_{wet}$ = 21,715

$92MY_{dry}$ = 72,361 $\qquad$ $91MY_{dry}$ = 85,810 .

So R_2 = 0.9016. This indicates that 1992 model year vehicles have, compared to 1991 model year vehicles, 9.8% lower crash risk when the pavement is wet compared to when it is dry; such model year effects of this magnitude are to be expected [1, 14].

An estimate, R, of the effect of ABS on crash rate correcting for the two confounding biases is defined by

$$R = R_1/R_2 , \qquad (4)$$

which, for the present example gives R = 0.7411/0.9016 = 0.8220. In using this measure we make the plausible assumption that the ramp-up effect for the ABS vehicles is the same as for 1992 model year vehicles in general. This is equivalent to assuming that the probability that a vehicle of specific model year was registered by a given month is independent of whether or not it has ABS.

It is often convenient to think of the percent reduction, E, in relative risk for ABS compared to *non*-ABS, defined as

$$E = 100(1 - R)\%. \qquad (5)$$

For the present example, E = 100(1 - 0.8220)%, or E = 17.80%. That is, ABS is associated with a 18% lower crash risk on wet pavement. The interpretation of E is similar to an effectiveness as defined for devices such as safety belts [1]. Positive values indicate a reduction in risk, and negative values an increase in risk.

General terminology

To facilitate comparisons between any unusual (adverse) condition and any standard (normal or comparison) condition, and to simplify error calculations, we introduce the following terminology (the corresponding quantities for the specific example are indicated in parenthesis):

n_1 = No. of crashes by ABS-equipped vehicles under the unusual condition (corresponds to A_{wet})

n_2 = No of crashes by ABS-equipped vehicles under the standard condition (A_{dry})

n_3 = No. of crashes by *non*-ABS-equipped vehicles under the unusual condition (N_{wet})

n_4 = No of crashes by *non*-ABS-equipped vehicles under the standard condition (N_{dry})

n_5 = No. of crashes by 1992 Model Year vehicles under the unusual condition ($92MY_{wet}$)

n_6 = No of crashes by 1992 Model Year vehicles under the standard condition ($92MY_{dry}$)

n_7 = No. of crashes by 1991 Model Year vehicles under the unusual condition ($91MY_{wet}$)

n_8 = No of crashes by 1991 Model Year vehicles under the standard condition ($91my_{dry}$) .

In terms of the above quantities R is defined as

$$R = \frac{n_1 \times n_4 \times n_6 \times n_7}{n_2 \times n_3 \times n_5 \times n_8} . \qquad (6)$$

Errors in R and E

In defining R (and R_1 and R_2), it is arbitrary whether we compare wet to dry, or dry to wet. If, say, the risk when wet was 2.0 times the risk when dry, then the risk when dry would be 0.5 times the risk when wet. The quantity R has a logical lower bound of zero, but no logical upper bound (E can be in the range from -∞ to 100%). Accordingly, the errors around the estimate of R (or E) are not symmetric. A measure possessing the desired symmetry is the log odds ratio [15], the logarithm of R. If we choose natural logarithms (to base e), represented by ln(R), then the standard error in the log odds ratio, $\sigma_{ln(R)}$, is given by

$$\sigma_{ln(R)} = \sqrt{\sum_{i=1}^{8} \frac{1}{n_i}} , \qquad (7)$$

where the summation is over the eight crash frequencies used to compute R. Substituting the specific example values gives $\sigma_{ln(R)} = 0.0566$. The major contribution to the error comes from the smallest number (in this case, $n_1 = 579$). The larger numbers, such as $n_8 = 85{,}810$ make a negligible contribution to the error. The upper and lower error limits on R are given by

$$R_{lower\ limit} = \exp[\log(R) - \sigma_{ln(R)}], \qquad (8)$$

$$R_{upper\ limit} = \exp[\log(R) + \sigma_{ln(R)}] . \qquad (9)$$

For the illustrative example, $R_{lower\ limit} = 0.7768$ and $R_{upper\ limit} = 0.8699$. Using eqn 5 we can express these values equivalently as $E_{lower\ limit} = 13.01\%$ and $E_{upper\ limit} = 22.32\%$. The lower limit of E corresponds to the upper limit of R.

When errors are small, the standard error in E, ΔE, is given approximately by

$$\Delta E = 100 \times R \times \sigma_{ln(R)} , \qquad (10)$$

which for the example is 100 x 0.8222 x 0.0566 = 4.65%.

For this example the result E = (17.80 ± 4.65)% is nearly identical to the result from computing the upper and lower limits individually. Results will generally be presented in this convenient (E ± ΔE)% form. When errors are too large for this approximation to be adequate, upper and lower limits will be given in the text.

All errors quoted are standard errors. The approximate interpretation is that the actual value is 68.26% likely to be within the quoted error limits, but has a 15.87% chance of being either higher or lower. Two standard errors correspond approximately to a 95% confidence limit (rather than the present 68%), and three standard errors to a 99% confidence limit.

RESULTS FOR OVERALL CRASH RISK

Roadway surface

The specific example used to illustrate the calculations appears as the top item in Table 2, and shows a (17.8 ± 4.7)% lower risk for ABS-equipped vehicles on wet roads. As the effect is well over three standard errors different from zero, it is extremely likely that ABS does reduce crash risk on wet roads. The combined estimate for a groups of states is obtained by adding the raw data from each of the states. This is equivalent to assuming that one composite jurisdiction provided all the data. Conceptually and computationally, this is the simplest procedure. In order to facilitate comparison with the previously published results in [12], the result for Texas and Missouri combined is given. All the raw data used for these states are given in [12].

Table 2.
Results for different roadway surface conditions compared to dry roadway

Condition	State	E ± ΔE, %
Wet	Texas	17.8 ± 4.7
	Missouri	5.7 ± 7.2
	TX & MO combined	**13.0 ± 3.9**
	North Carolina	4.5 ± 8.0
	Pennsylvania	13.8 ± 7.1
	Indiana	3.8 ± 7.8
	All 5 states combined	**10.4 ± 2.7**
Snow or ice	Texas	26.6 ± 20.3
	Missouri	-3.3 ± 16.0
	TX & MO combined	**3.7 ± 12.8**
	North Carolina	0.5 ± 41.2
	Pennsylvanian	2.1 ± 12.2
	Indiana	11.5 ± 13.9
	All 5 states combined	**6.3 ± 7.1**

All five states have positive values of E, giving the composite result that ABS reduces crash risk on wet roads by (10 ± 3)% (assuming no change in crash risk on dry roads).

When the roadway surface is snow or ice covered, sample sizes are substantially smaller, and a less clear pattern emerges. The composite estimate of (6 ± 7)% at most hints that ABS may reduce crash risk when the road is snow or ice covered.

Weather

Given that the road surface is coded as wet, there is about a 70% probability that the weather is coded as rain. Results for rain and other weather conditions are presented in Table 3. The results for all five states consistently indicate that ABS is associated with a reduced risk of crashing when it is raining (assuming no effect under clear weather). The combined result, (12 ± 2)%, is very similar to the result on wet compared to on dry pavement. No clear pattern emerges from the analyses of the other weather conditions shown in Table 3.

Table 3.
Results for different weather conditions compared to clear (including cloudy) weather

Condition	State	E ± ΔE, %
Rain	Texas	15.9 ± 5.6
	Missouri	8.7 ± 8.3
	TX & MO combined	**12.8 ± 4.7**
	North Carolina	6.6 ± 8.8
	Pennsylvania	20.0 ± 7.3
	Indiana	2.1 ± 9.5
	All 5 states combined	**11.6 ± 2.4**
Snow, Ice Sleet, or Freezing	Texas	60.9 ± 16.7
	Missouri	-5.0 ± 18.7
	TX & MO combined	9.6 ± 14.4
	North Carolina	-26.1 ± 56.4
	Pennsylvania	4.9 ± 13.1
	Indiana	-22.9 ± 19.0
	All 5 states combined	**-0.9 ± 8.4**
Fog	Texas	-39.1 ± 33.2
	Missouri	40.4 ± 18.6
	TX & MO combined	0.0 ± 18.6
	North Carolina	43.9 ± 27.1
	All 3 states combined	**7.6 ± 16.0**

Rollover risk

Table 4 shows results of comparing crashes involving overturn to all crashes except those involving overturn (essentially comparing rollover crashes to all crashes). Data from four of the five states associate ABS-equipped vehicles with increased rates of rollover crashes. The results for Texas and Indiana are, individually, close to two standard errors different from no effect. The composite effect is that the ABS-equipped vehicles have a (39 ± 16)% higher relative rollover risk. The one standard error lower and upper limits more appropriately computed by eqns 8 and 9 are 23% and 56%, respectively; the two standard

Table 4.
Results for crashes involving overturn, pedestrians, or animals. In each case the comparison is between crashes involving the stated factor and all other crashes not involving it. *For example, all crashes in which the* vehicle overturned are compared to all crashes in which the vehicle did not overturn.

Condition	State	E ± ΔE, %
Overturn	Texas	-50.7 ± 26.2
	Missouri	-27.1 ± 40.5
	TX & MO combined	**-44.4 ± 22.0**
	North Carolina	-9.1± 29.1
	Pennsylvania	25.9± 39.4
	Indiana	-92.5 ± 59.0
	All 5 states combined	**-38.7 ± 16.3**
Pedestrian	Texas	36.6± 17.7
	Missouri	29.8± 26.9
	TX & MO combined	33.9± 14.9
	North Carolina	-49.2 ± 68.4
	Pennsylvania	11.8± 19.6
	Indiana	41.5± 26.9
	All 5 states combined	**22.2± 11.0**
Animal	Texas	-27.7 ± 35.1
	Missouri	-15.8 ± 29.3
	TX & MO combined	**-20.8 ± 22.4**
	North Carolina	7.7± 17.2
	Pennsylvania	28.8± 27.4
	Indiana	3.4± 14.5
	All 5 states combined	**-1.2± 9.6**

error limits are 10% to 75%. If there were no effect, the probability that a value of R as large as observed would arise by chance is less than 1%. The data establish with some confidence that a higher relative rollover risk is associated with ABS.

Crashes with Pedestrians and Animals

Data from four of the five states associate ABS with a lower risk of pedestrian crashes (Table 4). The combined effect is (22 ± 11)%. The one standard error lower and upper limits more appropriately computed by eqns 8 and 9 are 11% and 32%, respectively; the 1.96 standard error limits are -3% and 41%, so the effect falls just short of being statistically significantly different from zero at the 5% confidence limit.

There are no consistent effects relating ABS and crashes involving animals (Table 4), though Kahane finds ABS associated with reduced risk of crashing with pedestrians and animals [16], and Farmer et. al [11] find a reduction in the risk of killing pedestrians, bicyclists and occupants of other vehicles. No associations between the risk of any type of injury and ABS were found [12]. The main results presented above are summarized in Table 5; the minor differences from Table 8 of [12] arise because of the addition of the data from NC, PA, and IN.

Table 5.
Summary of effects of ABS on some relative crash risks

Condition investigated	Comparison condition	Risk reduction associated with ABS
Wet roadway	Dry roadway	**(10 ± 3)%**
Raining	Clear or cloudy weather	**(12 ± 2)%**
Crashes involving pedestrians	All crashes not involving pedestrians	**(22 ± 11)%**
Crashes involving overturn	All crashes not involving overturn	**- (39 ± 16)%**

RISK OF FRONT AND REAR IMPACT IN TWO-VEHICLE CRASHES

Similar analysis procedures were used to investigate two-vehicle crashes in the same five states [13]. Each crash included in the analysis had a clearly defined lead vehicle (identified by rear damage) and a following vehicle (identified by frontal damage), thus enabling us to address the following questions: -

1. How does ABS affect a vehicle's risk of crashing into a vehicle it is following?
2. How does ABS affect a vehicle's risk of being struck in the rear?

Approach

Two sets of calculations were performed. In the first the influence of ABS on the ratio of front to rear impacts was determined. Let us call this the *Front-to-Rear* ratio. If it is assumed that ABS has no effect on the risk of being struck in the rear, then a lower *Front-to-Rear* ratio implies that ABS reduces the risk of striking a lead vehicle. However, if ABS has no effect on risk of striking a lead vehicle, then a lower *Front-to-Rear* ratio implies that ABS increases the risk of being struck in the rear. The *Front-to-Rear* ratio is a relative risk measure which does not distinguish between reduced front or increased rear impacts. However it has the advantages that it uses data efficiently, and its interpretation does not involve additional uncertain assumptions.

In the second set of calculations an attempt was made to estimate a more absolute risk of front and rear impacts by normalizing with respect to another crash type less likely to be influenced by ABS than either front or rear impacts. The other crash mode chosen was side impacts; this is equivalent to using side impacts as an induced exposure measure.

Calculations

Figure 1 illustrates the two crash types that are at the core of [13]. These crash types are more formally defined as

n_1 = the number of crashes in which an ABS-equipped vehicle sustained frontal damage in crashing into the rear of any vehicle

n_2 = the number of crashes in which an ABS vehicle was struck in the rear by any vehicle.

For any complete set of two-vehicle crashes (confined to one vehicle frontally striking another in the rear), the total number of vehicles struck in the rear is, by definition, identical to the total number of vehicles struck in the front. However, for subsets of crashes involving specific vehicles, no such equality applies. Rather, the departure from equality measures a differential tendency to be involved as either a striking or a struck vehicle.

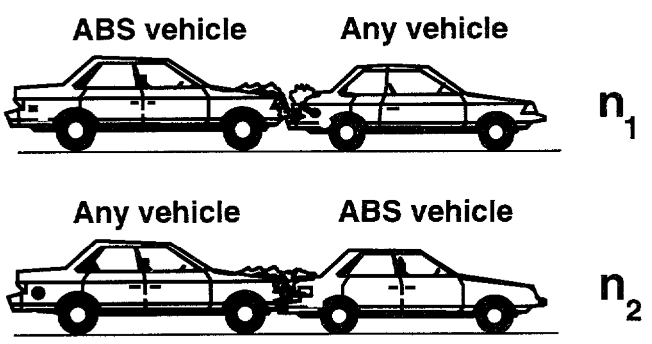

Figure. 1. Definitions of the two main crash types used to compute the *Front-to-Rear* ratio

We illustrate the calculation procedures using one specific numerical example, namely, Texas crashes on wet roads. For this case we have $n_1 = 44$ and $n_2 = 75$. These values nominally indicate that the ABS vehicles are 0.59 times as likely to be struck in the front as in the rear. However, this difference cannot be attributed to ABS alone. The *non*-ABS versions of the seven specific vehicles contributing to the study are not expected to have identical numbers of front and rear impacts (*non*-ABS refers to the 1991 model year versions of the seven vehicles in Table 1, and not to other vehicles without ABS). We must therefore compare the ratio of n_1 to n_2 for the ABS vehicles to the corresponding ratio for these same vehicle makes without ABS. To achieve this we introduce

n_3 = the number of crashes in which a *non*-ABS-equipped vehicle sustained frontal damage in crashing into the rear of any vehicle, and

n_4 =the number of crashes in which a *non*-ABS vehicle was struck in the rear by any vehicle.

For Texas $n_3 = 151$ and $n_4 = 108$, so that on wet roads the *non*-ABS vehicles were 1.40 times as likely to be struck in the front as in the rear. The large departure of this ratio from unity reflects a general pattern in which on wet roads smaller cars have large *Front-to-Rear* ratios whereas large cars and trucks have small *Front-to-Rear* ratios. This pattern was found to be highly robust, based on considerable analyses of the same state data used in this study. To obtain the effect of ABS we divide the *Front-to-Rear* for the ABS vehicles by the corresponding ratio for the *non*-ABS vehicles. Therefore, we obtain the result that, compared to the *non*-ABS vehicles, the ABS vehicles are 0.59/1.40 = 0.42 times as likely to be struck in the front as in the rear.

The above comparison of ABS and *non*-ABS vehicles involved comparing risks in 1992 to risks in 1991 model year vehicles. As there are systematic differences dependent on model year [1,14], we correct for this model year effect by introducing

n_5 = the number of crashes in which a 1992 MY vehicle sustained frontal damage in crashing into the rear of any vehicle

n_6 = the number of crashes in which a 1992 MY vehicle was struck in the rear by any vehicle

n_7 = the number of crashes in which a 1991 MY vehicle sustained frontal damage in crashing into the rear of any vehicle

n_8 = the number of crashes in which a 1991 MY vehicle was struck in the rear by any vehicle.

The values for Texas on wet roads are: $n_5 = 1703$; $n_6 = 2130$; $n_7 = 2345$; and $n_8 = 2626$. These values give $n_5/n_6 \div n_7/n_8 = 0.89$, which means that 1992 MY vehicles are, compared to 1991 MY vehicles, 0.89 times as likely to be struck in the front as to be struck in the rear. Dividing the previous 0.42 ratio by this value gives that the ABS vehicles are 0.47 times as likely to be struck in the front compared to being struck in the rear. Thus, we find that on wet roads in Texas, there is a *Front-to-Rear* ratio of 0.47 that is specifically attributable to ABS, or, equivalently, E = 53%.

The above calculation of the *Front-to-Rear ratio*, R, can be stated more formally as

$$R = \frac{n_1 \times n_4 \times n_6 \times n_7}{n_2 \times n_3 \times n_5 \times n_8} . \qquad (11)$$

This is identical to eqn 6 (with the present definitions of n_1 through n_8 replacing the earlier definitions), so the computation of errors and other quantities follow as before.

RESULTS FOR WET ROADS

Ratio of Front Impact to Rear Impact crashes

The example above appears as the first entry in Table 6. The corresponding results for the other four states are entered below this value (the raw numbers from which all values in Table 6 were computed are given in [13]). For all five states E is positive. For TX and MO the values of E have high statistical reliability, being 3.2 and 5.3 standard errors different from no effect. The probabilities that the E values for the remaining three states (NC, PA, & IN) are individually positive are 65%, 91%, and 92% (compared to 56%, 9%, and 8%, respectively, that they are negative). Thus all the five states show consistently that on wet roads a vehicle with ABS is less likely to crash into a vehicle it is following compared to its own risk of being struck in the rear. The result of combining the data from all five states is E = (48.0 ± 6.0)%.

Table 6.
Two vehicle crash results for WET roads.

	Reduction in risk for ABS vehicles, E ± ΔE (%)				
	Front Rear			Front Side	Rear Side
State	All lead vehicles	Lead vehicle stopped	Lead vehicle moving	All lead vehicles	All lead vehicles
TX	52.8 (11.0)①	63.6 (11.3)	50.8 (23.2)	38.8 (12.3)	-29.7 (23.7)
MO	79.8 (6.0)	75.1 (11.0)	83.4 (7.7)	64.8 (10.3)	-74.1 (39.3)
NC	11.0 (26.5)	42.3 (23.8)	24.0 (44.4)	22.5 (23.0)	12.9 (25.3)
PA	31.0 (19.2)	16.6 (34.8)	*	40.2 (23.0)	13.3 (32.4)
IN	28.5 (17.0)	38.6 (30.2)	24.0 (31.6)	25.8 (22.5)	-3.9 (30.6)
ALL	**48.0 (6.0)**	**55.5 (7.9)**	**57.2 (9.8)**	**32.2 (7.7)**	**-30.4 (13.6)**

① One standard error shown in parenthesis

*** Insufficient data**

The individual state results vary somewhat more than expected by chance in this case, in keeping with generally observed differences between quantities observed in different state files. In terms of 95% confidence limits, only the MO result (R between 0.11 and 0.36) is inconsistent with the overall average (R between 0.41 and 0.65). It could be argued that, from a formal statistical viewpoint, it is inappropriate to aggregate data showing such a degree of heterogeneity, and that the only results that should be reported are those for individual states. Hauer [17] presents convincing arguments opposing this view, and stresses the central importance of providing aggregate estimates even in the face of formal obstacles. Because of the heterogeneity in the results from the individual states, the standard error of the aggregate estimate will be underestimated. One way to obtain a more appropriate standard error would be to increase the estimates of the standard errors of the individual states by a quantity reflecting a judgmental estimate of the effect of sources of variability beyond those due to statistical fluctuations in the frequency counts [18]. Because of the arbitrary nature of the choice of the additional variability for each state, we will not do this here. The aggregate estimate we use was obtained by adding the raw data, which is equivalent to assuming that one composite jurisdiction provided all the data; conceptually and computationally, this is the simplest procedure. Another way to obtain a composite estimate is to assume that each state provides an independent estimate, and obtain an average by weighting each state estimate by the reciprocal of the square of its standard error. Such a procedure [19] yields (45.8 ± 6.4)%, not materially different from the result (48.0 ± 6.0)% which we use.

The result E = (48.0 ± 6.0)% is 5.6 standard errors different from no effect. Thus, even with the reservation that the standard error may be somewhat underestimated, this result still provides evidence at an extremely high level of reliability of a substantial difference dependent on the presence of ABS. If we assume that ABS does not affect the risk of being struck in the rear, then it essentially halves the risk of crashing into a lead vehicle. It is rare for an effect of this magnitude to be associated with any vehicular attribute.

Lead vehicle stopped. When the lead vehicle is coded as being stopped (but not parked) the five states again consistently show large positive values of E (Table 6). The combined result for all five states is that on wet roads an ABS-equipped vehicle is (55.5 ± 7.9)% less likely to run into the rear of a stationary vehicle than it is to be struck in the rear when stationary. Note that the probability that a stationary vehicle is struck in the rear is expected to depend somewhat on its braking capabilities. The greater the stopping deceleration used, the longer is the period during which the vehicle is stationary. Observational studies [20] found newer cars used higher levels of deceleration when stopping at intersections, an effect likely related to superior braking capability, and a pattern likely to increase the risk of being rear impacted.

Both vehicles moving. For the case in which both vehicles were coded as moving in the same (forward) direction there were insufficient cases in PA to perform this analysis. The four remaining states consistently show large positive values of E, with a combined result that on wet roads an ABS-equipped vehicle is (57.2 ± 9.8)% less likely to run into the rear of a moving lead vehicle than it is itself to be struck in the rear when moving.

Use of Side Impact Crashes to Estimate Absolute Effects of ABS

The above estimates are all relative in the sense that the risk of front impact is expressed only relative to the risk of rear impact. A value of E = 50% could arise if ABS halved the risk of crashing into a lead car while not affecting the risk of being rear impacted. However, the identical value would arise if ABS did not affect the risk of crashing into a lead vehicle, but doubled the risk of being rear impacted. In order to separate the two components of the *Front-to-Rear* ratio, we use an induced exposure measure, in which the number of side impacts sustained by a set of vehicles is used to estimate the presence of those vehicles in the traffic stream. Using side impact crashes to measure exposure involves the crucial assumption that the risk of a vehicle being struck in the side is not affected by whether or not the vehicle is equipped with ABS. While such an assumption is clearly an approximation, it is nonetheless likely to be sufficiently correct to identify large effects.

The *Front-to-Side* ratio has positive values of E for all five states, implying that on wet roads a vehicle equipped with ABS is less likely to crash into a vehicle it is following than is a vehicle not so equipped (Table 6). The calculation is as before, except that n_2, n_4, n_6, and n_8, refer to crashes in which the vehicle is struck in the side rather than in the rear. Combining the data for all states gives the result that ABS reduces the risk of crashing into a lead vehicle by $(32.2 \pm 7.7)\%$.

For the *Rear-to-Side* ratio the results for MO and TX are statistically significantly different from zero effect at the $p < 0.01$ and $p < 0.1$ levels of confidence, respectively, and each indicates an increased risk of being struck in the rear to be associated with ABS. The uncertainty (due to small sample sizes) for the other states is too great to suggest any effect. Combining data for all five states gives the result that an ABS equipped vehicle is $(30.4 \pm 13.6)\%$ more likely to be struck in the rear than a vehicle without ABS.

RESULTS FOR DRY ROADS

Table 7 summarizes the results of an analysis parallel to that described above, but for crashes on dry roadway. Overall *Front-to-Rear* ratio shows no indication of any effect dependent on ABS. For the case of both vehicles moving, there is a suggestion of an increased risk of crashing into the rear of a lead car.

Table 7.
Two vehicle crash results for DRY roads

	Reduction in risk for ABS vehicles, $E \pm \Delta E$ (%)				
	Front / Rear			Front / Side	Rear / Side
State	All lead vehicles	Lead vehicle stopped	Lead vehicle moving	All lead vehicles	All lead vehicles
TX	-4.6 (11.2)①	1.6 (14.2)	-22.9 (25.6)	-4.8 (8.8)	-0.2 (9.0)
MO	5.8 (14.3)	1.8 (22.4)	3.3 (22.5)	-4.4 (14.2)	-10.8 (14.9)
NC	12.6 (15.6)	30.1 (16.9)	-41.5 (50.9)	-6.7 (17.1)	-22.1 (18.5)
PA	3.5 (14.6)	4.0 (21.2)	*	25.7 (14.5)	23.0 (15.0)
IN	-11.8 (17.0)	33.4 (22.4)	-53.0 (40.9)	-1.0 (17.9)	9.7 (16.1)
ALL	**0.1 (6.3)**	**10.3 (8.4)**	**-23.2 (15.4)**	**-2.6 (5.7)**	**-2.7 (5.7)**

① One standard error shown in parenthesis

*** Insufficient data**

IS ABS ASSOCIATED WITH INCREASED AVERAGE TRAVEL SPEED?

The earlier papers [12,13] raised the possibility that ABS (and braking improvements in general) might be associated with increased average travel speed. Such an effect would help explain why observed reductions in crash rates are generally less than those expected based on the technical improvements in braking provided by ABS.

Inference from anecdotal information

I have asked audiences attending a number of technical presentations if they thought their driving changed because their vehicle was ABS-equipped, and have posed the same question to many acquaintances (neither group is a random sample of drivers). The following observations are based on a few hundred responses.

1. None indicated with confidence that they ever drove slower under any conditions because their vehicle was ABS-equipped.
2. Many indicated that, under certain circumstances, they were confident that they sometimes drove faster if their vehicle was ABS-equipped.

I can personally attest that I am unaware of any case in which I have ever driven slower because my vehicle had ABS. On the other hand, I have driven faster on many occasions because my vehicle was ABS equipped. For example, when driving on slush on a narrow two lane road, with oncoming traffic a few feet to my left and a deep drainage ditch a few feet to my right. My experience with non-ABS brakes tells me to severly reduce speed because even light non-ABS braking could place me in the path of uncoming traffic or in the ditch. My speed reduction is far larger than appropriate for a vehicle with the excellent lateral control that ABS so effectively provides. (My comment on page 310 of [1] that this researcher of traffic crashes has never actually experienced one remains intact at time of writing). ABS is a successful and effective automotive technology that drivers can use to increase mobility efficiency as well as safety.

The above audience, acquaintances, and personal anecdotal information suggests the following two postulates:

Postulate 1: No drivers ever drive slower because their vehicles have ABS.

Postulate 2: Some drivers, under some circumstances, sometimes drive a little faster because their vehicles have ABS.

If we accept these two postulates, then it follows with rigorous logic that, on average, all other factors being equal, ABS-equipped vehicles are driven at higher average speeds than non-ABS vehicles.

Postulate 1 need not be satisfied for the conclusion to follow provided the speed increase exceeds the speed decrease (both appropriately weighted). Thus the conclusion that ABS is associated with an increase in average speed should be viewed as inescapable. However, it is the magnitude of the effect, and the circumstances under which it occurs, that is crucial for safety.

Preliminary examination of ABS and speed law convictions using Oregon data

An attempt was made to examine empirically whether ABS-equipped vehicles were associated with higher rates of conviction for speed-related offenses than were non-ABS vehicles. Data were obtained from Oregon because this state's files enabled linkage between driving records and vehicle ownership.

Table 8 shows convictions by drivers who were owners of 1991 or 1992 models of the seven vehicles listed in Table 1. The nominal indication is that the drivers who owned ABS vehicles had (18 ± 10)% more convictions for speeding, compared to non-speeding offenses than the non-ABS vehicles. From a formal statistical perspective this is a clear effect. The data were used to examine only one hypothesis, and this hypothesis was stated prior to obtaining the data, and turns out to be statistically significant at $p<0.05$. However, for two main reasons the result should be interpreted with the utmost caution.

Table 8.

Oregon police convictions for offenses relating to excessive speed compared to other offenses for drivers who were registered owners of the ABS and non-ABS model vehicles listed in Table 1

	Number of convictions by drivers who own:-	
	ABS vehicles	non-ABS vehicles
Speed offenses	670	801
Unrelated to speed	419	591
Speed offenses / Non-speed offenses	1.60	1.36

First, some unknown fraction of the convictions were obtained driving a different vehicle than the one indicated (the driver may have owned additional vehicles, or have driven a borrowed vehicle). The convictions file did not contain vehicle information as such. It included the driver license. The driver license number of the registered owner was also included in the vehicle file. It can be argued that an effect such as this would tend to dilute the strength of any real effect, so that if the sample could be confined exclusively to convictions in the indicated vehicles, the effect would be larger.

Second, there is the even more important problem that the effect apparent in Table 8 could be due to the ABS and non ABS vehicles being also of different model year. There is reason to expect differences in driver behavior to be associated with model year regardless of ABS [1,14], effects that were corrected for in [12,13]. The limited scope of this pilot examination precluded obtaining the necessary data to normalize for model year effects unrelated to ABS.

Because of the substantial uncertainties in interpretation and the caveats expressed above, the data in Table 8 should be interpreted as little more than suggesting the possibility of an effect of sufficient magnitude to justify a more complete and rigorous investigation along similar lines in the hope of further illuminating the relationship between ABS and travel speed, and of broader driver behavior questions.

DISCUSSION

When driving on wet pavement ABS is associated with a (10.4 ± 2.7)% reduction in crash risk, assuming that ABS has no effect on crash risk on dry pavement. If we assume that 20% of all crashes occur on wet roads, then this result implies that ABS would reduce crash risk, overall, by (2.1 ± 0.5)%. Such an effect is consistent with earlier studies that reported no observed effect, because the data and methods of those studies [6,9] lacked the precision necessary to detect a reduction of this size. A reduction of 2% is of course an important effect, if real. The conclusion that such a reduction is real depends on the assumption that ABS has no effect on crash risk when the road is dry; one study [10] reports a 6% to 8% reduction on dry roads.

The finding that ABS equipped cars were associated with a (39 ± 16)% higher rollover risk could be due to a combination of factors. It is possible that the improved steering control provided by ABS could in some circumstances convert non-rollover crashes into rollover crashes. For example, a high-speed out of control non-ABS car might be immobilized after striking a tree, whereas if ABS were available, the greater steering control might enable the driver to miss the tree and thereby continue to travel at high speed in off-roadway terrain with consequent risk of rollover. It is possible that the very steering control that ABS provides allows steering inputs that translate into rollover, whereas the non-ABS-equipped vehicle will skid out of control until striking some object. It is also possible that ABS is associated with some small change in driver behavior which increases rollover risk, a likely candidate being a small increase in average travel speed. Anecdotal evidence and an uncertain and tentative analysis of some Oregon traffic conviction data support such a possibility. Test track experiments provide direct evidence that drivers of vehicles equipped with ABS choose higher travel speeds [21].

An investigation of the vehicle-following behavior of 213 taxis in Norway found that drivers of ABS-equipped vehicles followed at shorter headways than did those without ABS [22]. Speed was too constrained by traffic conditions to allow any effects due to ABS to be examined in this study. However, earlier research [1,23] finds that crash rates are related to headways and to travel speeds in similar ways. Thus [22] can be interpreted to provide indirect evidence that ABS is associated with higher speeds.

The finding in [8] of an increase in claim severity is likewise consistent with the possibility of increased speed. Because rollover risk is extremely sensitive to travel speed, even a small speed increase could produce a large increase in rollover risk. If such a small increase in travel speed was associated with ABS, then average crash risk on dry roads might be slightly higher, perhaps by a percent or so. It would be extremely difficult to address this question directly. Increased speeds in test-track experiments may not necessarily translate into increased speeds in actual driving. In this regard it is notable that a 1% increase in speed has been observed to be associated with safety-belt wearing in an instrumented vehicle study [24]. Changes of this magnitude are important, but extremely difficult to observe directly in actual traffic.

How reasonable is it to expect that the availability of ABS might lead to changes in driver behavior? The 1938 volume of the American Journal of Psychology contains the following comment:

> **More efficient brakes on an automobile will not in themselves make driving the automobile any safer. Better brakes will reduce the absolute size of the minimum stopping zone, it is true, but the driver soon learns this new zone and, since it is his field-zone ratio which remains constant, he allows only the same relative margin between field and zone as before. [25]**

Research conducted in the more than half a century since this was written does not support the implied suggestion that improved braking cannot affect overall crash risk. However, it does establish that technical innovations that lead to observable differences in vehicle performance or handling characteristics are likely to be accompanied by changes in driver behavior.

An extensive discussion such human behavioral responses is given in Chapter 11 of [1]. Because of the self-controlled nature of the driving task, the driver may use technical improvements to generate benefits other than safety. Two observational studies [14,20] indirectly suggest that improved braking may be used for purposes other than safety. In both, car age serves as a surrogate for braking, because it is plausible that as vehicles age, their stopping distances increase as tires and brakes deteriorate.

Observed driver behavior [20] at two signalized intersections showed that when cars stopped, drivers of newer cars used higher levels of deceleration than drivers of older cars. When cars proceeded, drivers of newer cars were more likely than were drivers of older cars to enter the intersections after the onset of red (that is, to be in violation of the traffic code). The authors write "It is possible that the drivers of older vehicles are adjusting their behaviour to compensate for the reduced mechanical condition of their vehicles" [20, p. 569].

An examination of rear-end crashes [14] showed a regular pattern in which the probability that a car was struck in the rear, given that it was involved in a crash, declines systematically with car age. If a seven year old car was involved in a crash, the probability that it was struck from the rear is about 30% lower than the corresponding probability for new cars. Thus the findings of these two studies [14,20] suggest behavioral responses to cars being in newer condition, with better braking likely the dominant factor. These results, together with the Munich taxicab result [6], suggest that drivers may be using the technical superiority of ABS to achieve benefits other than overall risk reduction. From a formal economic perspective, a technical innovation that the driver can choose to use in different ways is of higher value than one for which there is one prescribed use, such as safety (a ten dollar gift certificate valid only in a bookstore is of less value than ten dollars, which can be spent anywhere, including the bookstore).

There are many possible uses of a technological innovation like ABS beyond the reduction in overall crash risk. Anecdotally, we have heard drivers make comments like "I would not have gone out if I did not have ABS." If overall crash risk remains unaltered, but trips that would otherwise have been canceled are driven, then ABS has clearly provided an overall benefit even though overall crash risk has remained unchanged.

Various mechanisms can lead to ABS influencing driver behavior. Suppose a driver makes an emergency stop on a snow-covered road. If the driver is inexperienced on snow and is driving a non-ABS-equipped vehicle, a negative experience such as a skid or even, on much rarer occasions, a crash may result. Such feedback will encourage the driver to approach snow-covered roads with increased caution in the future. On the other hand, if the vehicle has ABS it is more likely to remain under control. Thus ABS drivers, regardless of their knowledge of ABS [26], will receive feedback that their driving was appropriate, and, according to one theory of driver behavior [27], will approach a similar situation in the future at a slightly higher speed.

At about the same time as the studies reported here were being performed, Kahane [28] was addressing the same questions. He used data from two (MO and PA) of the five states used here, plus Florida. He used calendar years 1990-1992 compared to our 1992-1993. He used 48 make-model subseries of 1985-1992 model year vehicles, compared to the seven 1991 and 1992 model year vehicles used here. There are many differences in detail, technique, approach, analysis and assumptions between the two studies. Overall the results are in remarkable agreement. For example, Kahane reports a statistically reliable 49% increase in rollover risk to be associated with ABS, compared to our finding of a (39 ± 16)% increase. The degree of agreement increases confidence that the effects reported are real changes in crash risk that are associated with ABS in general, and do not depend on the specific vehicles, states, years of data, or methods of analysis.

Additional information on the relationship between rollover risk and ABS is provided by Hertz et al. who report a significant increase in fatal rollover crashes to be associated with ABS for passenger cars [29], but a significant reduction in non-fatal rollover risk for light trucks with all-wheel ABS systems [30]. Lau and Padmanaban [10] also find ABS to be associated with increased rollover risk. Their study, which uses police reported crashes per registered vehicle, generally finds larger risk reductions to be associated with ABS than other studies; they report a 6% to 8% reduction on dry roads and a 17% to 19% reduction on wet roads. Farmer et al. [11] suggest these values may be related to possible limitations of [10], especially as such large differences would be expected to lead to reductions in insurance claims larger than is consistent with direct examinations of insurance claims [9].

SUMMARY OF ABS EFFECTIVENESS STUDIES

The many different measures, methods, data sets, weather conditions, crash types, crash severities, etc. used in the studies discussed above makes it difficult to effectively synthesize all available findings. Tables 9-11 present the results in a format aimed at facilitating comparisons and supporting general conclusions.

For dry roads, only two of the entries in Table 9 indicate a statistically significant reduction in risk, compared to six indicating a risk increase. The general pattern in Table 9 suggests it is unlikely that on dry roads ABS can materially reduce risk.

The wet road results (Table 10) indicate a statistically significant decrease in risk for nine entries, compared to an increase for four, suggesting that ABS materially reduces risk on wet roads. ABS leads to a substantial reduction in the risk of crashing into a followed vehicle on wet roads, but with a corresponding increase in the risk of being struck by a following vehicle.

For all roadway conditions (Table 11), the first entry in the table indicates no observed difference in overall insurance claims to be associated with ABS [9]. If ABS reduces risk on wet roads, as the evidence supports, then no observable effect on total crash risk precludes the possibility that ABS is reducing risk on dry roads. The assumption used earlier of zero effect on dry roads thus seems to be a reasonable approximation.

A consistent finding in each of Tables 9-11 is that ABS is associated with increased rollover risk, and with increased

Table 9.
Summary of estimates in the cited studies[1] of the percent change in risk associated with ABS when driving on DRY roads. The interpretation of the first entry is that ABS is associated with a 54% increase in rollover risk.

Results for DRY roads

			ALL CRASHES (Single or multiple vehicle)							MULTI-VEHICLE CRASHES					
			All crash types			Rollover		Pedestrian bicycle, etc.		All		Striking lead vehicle		Struck by foll. veh.	
Author [Ref.]	Measures	Data	Fatalities in ABS vehicle	Fatal[2]	All	Fatal	All	Fatal	All	Fatal	All	Fatal	All	Fatal	All
HLDI [9]	Insurance claims / Insured vehicle	Insurance claims													
Evans [12]	Risk one condition / Risk in another	MO,TX[3]													
Kahane [28]	Relevant / Non-Relevant	FL,MO,PA FARS					+54			0	0	+5	+1		-1
Hertz et al. [29]	Relevant / Non-Relevant	FL,MO,PA FARS				+54	+27						-9		
Evans and Gerrish [13]	Relevant / Non-Relevant	IN,MO,NC PA,TX											+3		+3
Lau and Padmanaban [10]	Crashes or fatalities / Registered vehicle	FL,PA,NC FARS, Polk			-7										
Farmer et al. [11]	Fatal Crashes / Registered vehicle	FARS R.L. Polk	+23	+15		+65 [4]			+1	+5					
Evans This paper	Risk one condition / Risk in another	IN,MO,NC PA,TX													

KEY

+54 ←% change at top **Increase** in risk

-9 **Decrease** in risk ←% change at bottom

+5 Nominal % increase at top. Authors report ***not-statistically significant*** result. Nominal % decrease at bottom

[1] Studies are listed in order of public availability.
[2] A fatal crash is one in which anyone is killed.
[3] Police reported crashes in states indicated by postal codes.
[4] Analysis restricted to fatalities in rollover vehicle -- fatalities to those not in the rollover vehicle are rare.

Table 10

Summary of estimates in the cited studies① of the percent change in risk associated with ABS when driving on WET* roads. The interpretation of the first entry is that ABS is associated with a 13% reduction in crash

Results for WET* roads

Author [Ref.]	Measures	Data	ALL CRASHES (Single or multiple vehicle): All crash types: Fatalities in ABS vehicle	All crash types: Fatal②	All crash types: All	Rollover: Fatal	Rollover: All	Pedestrian bicycle, etc.: Fatal	Pedestrian bicycle, etc.: All	MULTI-VEHICLE CRASHES: All: Fatal	All: All	Striking lead vehicle: Fatal	Striking lead vehicle: All	Struck by foll. veh.: Fatal	Struck by foll. veh.: All
HLDI [9]	Insurance claims / Insured vehicle	Insurance claims													
Evans [12]	Risk one condition / Risk in another	MO,TX③			-13										
Kahane [28]	Relevant / Non-Relevant	FL,MO,PA FARS					+34			-14	-24		-39		+27
Hertz et al. [29]	Relevant / Non-Relevant	FL,MO,PA FARS				+14	+94					-35	-35		
Evans and Gerrish [13]	Relevant / Non-Relevant	IN,MO,NC PA,TX											-32		+30
Lau and Padmanaban [10]	Crashes or fatalities / Registered vehicle	FL,PA,NC FARS, Polk			-18										
Farmer et al. [11]	Fatal Crashes / Registered vehicle	FARS R.L. Polk	+40	+18		+53 ④			-10	+13					
Evans This paper	Risk one condition / Risk in another	IN,MO,NC PA,TX			-10										

KEY

+34 (dark shading) ← % change at top — **Increase** in risk

-13 (vertical hatching) — **Decrease** in risk ← % change at bottom

+14 (unshaded) — Nominal % increase at top. Authors report ***not-statistically significant*** result. Nominal % decrease at bottom

*Definitions vary between studies -- some include snow, ice, slick, and even gravel roads (expected to have unimportant effect because of its rarity)

① Studies are listed in order of public availability.

② A fatal crash is one in which anyone is killed.

③ Police reported crashes in states indicated by postal codes.

④ Analysis restricted to fatalities in rollover vehicle -- fatalities to those not in the rollover vehicle are rare.

Table 11.

Summary of estimates in the cited studies[1] of the percent change in risk associated with ABS when driving under any roadway conditions. The interpretation of the first non-zero entry is that ABS is associated with a 44% increase in rollover risk.

Results for all roadway conditions combined

			ALL CRASHES (Single or multiple vehicle)							MULTI-VEHICLE CRASHES					
			All crash types			Rollover		Pedestrian bicycle, etc.		All		Striking lead vehicle		Struck by foll. veh.	
Author [Ref.]	Measures	Data	Fatalities in ABS vehicle	Fatal[2]	All	Fatal	All	Fatal	All	Fatal	All	Fatal	All	Fatal	All
HLDI [9]	Insurance claims / Insured vehicle	Insurance claims			0										
Evans [12]	Risk one condition / Risk in another	MO,TX[3]					+44		-34						
Kahane [28]	Relevant / Non-Relevant	FL,MO,PA FARS		-2	-3	+40	+49	-27	+3		0				
Hertz et al. [29]	Relevant / Non-Relevant	FL,MO,PA FARS				+60	+24		+3						
Evans and Gerrish [13]	Relevant / Non-Relevant	IN,MO,NC PA,TX													
Lau and Padmanaban [10]	Crashes or fatalities / Registered vehicle	FL,PA,NC FARS, Polk		0	-9.5	0	+11								
Farmer et al. [11]	Fatal Crashes / Registered vehicle	FARS R.L. Polk	+26	+16		+63[4]			-1	+7					
Evans This paper	Risk one condition / Risk in another	IN,MO,NC PA,TX					+39		-22						

KEY

+44 ←% change at top **Increase** in risk

-34 **Decrease** in risk ←% change at bottom

-2 Nominal % increase at top. Authors report ***not-statistically significant*** result. Nominal % decrease at bottom

[1] Studies are listed in order of public availability.

[2] A fatal crash is one in which anyone is killed.

[3] Police reported crashes in states indicated by postal codes.

[4] Analysis restricted to fatalities in rollover vehicle -- fatalities to those not in the rollover vehicle are rare.

involvement in some types of fatal crashes. Behavioral changes, particularly speed increases, may contribute to these effects.

Many studies, observations, and inferences indirectly support or suggest that ABS may be associated with higher average speeds. Taken together, all the available evidence renders inescapable the conclusion that overall average speeds increase somewhat as a result of the superior capabilities provided by ABS.

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