Motorcycle Accident Reconstruction
Part I - Physical Models

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ABSTRACT

The purpose of this paper is to evaluate different formulas which are used to estimate the motorcycle's pre-collision speed in motorcycle-to-car accidents. These formulas are based on measurable physical parameters such as motorcycle' wheelbase change and fundamental physical laws such as conservation of momentum.

The evaluation used data from crash experiments performed by the authors as well as published experimental data. The results of these evaluations indicate that the motorcycle's pre-collision speed cannot be estimated with high accuracy.

Keywords

Motorcycle Accidents, Motorcycle Accidents Reconstruction, Vehicle Accidents.

1. INTRODUCTION

According to the National Highway Traffic Safety Administration (NHTSA), in 1969, there were 2.3 million motorcycles registered in the United States. This number increased dramatically during the next 40 years and currently there are over seven million motorcycles registered in the United States. Obviously, as the number of motorcycles on the road increased, so did the accident rate. In 1969, there were 69,500 motorcycle accidents reported, in which 1,855 persons were killed. In 2004, 4,008 motorcyclists were killed in the US, an 8% increase from 2003. The death rate per 100 million vehicle miles traveled for a motorcyclist is over 35 times higher than of an automobile occupant [1]. One of the main and unequivocal reasons motorcyclists are killed in crashes is because the motorcycle itself provides virtually no protection in a crash. For example, approximately 80 percent of reported motorcycle crashes result in injury or death while a comparable figure for automobiles is about 20 percent.

The earliest and the most frequently cited testing was published by Severy in 1970 [2], which included one test at 20mph, one test at 40mph, and 5 tests at 30mph. That paper included a chart showing a linear relationship between wheelbase reduction and speed with high correlation factor of 0.975. The Severy data is not relevant to today's motorcycles: chassis design, wheels, materials, engine mounting, and front end suspension styles have changed enough that his data is not applicable.

In 1976, Professor Harry Hurt [3] of the University of Southern California conducted a study of 3,600 motorcycle accidents in the Los Angeles area. The results of this study have become the basis for much motorcycle rider training and research. The study found that in 65 percent of the multi-vehicle cases the automobile violated the motorcycle right of way. A similar survey conducted by the Philadelphia police Department showed that such a violation is the cause in only 45 percent of all motorcycle accidents in the city of Philadelphia. Hurt's study also found that in 64 percent of single-vehicle motorcycle accidents, the operator was responsible for his accident. The majority of accidents occurred on a clear, dry day during daylight hours and typically, the motorcycle operator had less than six months riding experience and no formal training.

For many years there has been some controversy over the use of conservation of linear momentum to estimate the speed of motorcycles involved in collisions with other motor vehicles. Fricke and Riley stated in [4] that "occasionally a momentum analysis is attempted" and that this technique "rarely… works well" in accurately estimating the speed of the motorcycle. They explained that the heading and departure angles become sensitive "when the angles of approach are nearly collinear and the weight difference between the colliding vehicles is fairly large."

In 1990, Brown and Obenski write that a momentum analysis "can sometimes be used in motorcycle accidents," and give a graphical example of a momentum vector diagram of a motorcycle/automobile collision. [5]

In 1994, Obenski [6] further clarified this position by stating "Generally it is tricky to use momentum analysis in accidents between vehicles with a big weight difference," but gives the same graphical example as in his previous work. Obenski specifically cautioned against using a momentum analysis where the automobile has been moved very little after impact with the motorcycle.

In 1990, Niederer [7] wrote about techniques that may be used to reconstruct motorcycle/vehicle collisions, with the emphasis of the paper on the use of conservation of linear and angular momentum. Niederer specifically cautioned that "due to the often unfavorable mass ratio an accurate reconstruction may be impeded," but concluded that when used cautiously, the use of momentum and other available information "represents a powerful tool for motorcycle-vehicle collision reconstruction." He further concluded that reconstructionists should assess the sensitivity of the momentum analysis to changes in variation of impact configuration and post impact trajectory.

In [8] the principles of linear and angular momentum conservation were investigated. It was concluded that “Use of the sensitivity analysis will allow the reconstructionist to determine if the techniques should be applied to the given analysis or be abandoned in favor of other methods of speed analysis”.

In [9], the validity of 10 different relationships, which are to evaluate a motorcycle’s pre-collision speed strikes a passenger car, were evaluated. In contrary to expectations, the correlations between speed and crush were always stronger than any relations involving energy. When contemplating speed-from motorcycle-crush, it has been commonly assumed that that the type of wheel, cast or spiked, was an important consideration. This analysis showed that while wheel type does affect the motorcycle-to-car crush ratio, the total crush was not significantly affected.

The equations that most accurately predicted the reported impact speed of the test motorcycles were the Eubanks-form equations, with the modifications suggested by this analysis that account for the differences between the door/fender impact areas and the pillar/axle areas. The door/fender collision speeds were found to be predicted with a 95% confidence range of plus or minus 20% of the nominally calculated value, while the pillar/axle speeds were predicted within a range of plus or minus 28%.

From accident reconstruction point of view there is a limited amount of data, compared with vehicle collision data which makes accurate modeling very difficult. Collision tests involving cars moving at high enough speeds to affect the motorcycle’s trajectory are very rear. In these cases it appears to reduce the total measured crush, such that using the relationships developed here will under predict speeds, typically by 15%. The additional complication of a moving target vehicle also increases the data spread significantly. The limited car-bumper impact testing appeared to be very similar in crush characteristics to the pillar/axle impacts, but the data set was too small for significant analysis.

This paper provides analysis of test results of 13 different tests in which the motorcycles were crushed into the side of a car. The impact velocity ranged from 40-58[mph] and the impact point on the car varied. The motorcycle’s wheelbase change, width and the maximum indentation and the movement of the vehicle were recorded. In addition, data from previous 56 tests were used to check the analysis results.

1. CRASH TESTS

Sixteen motorcycles were used in the crash-tests. Figure 1 shows some photos these motorcycles. The data collected for each test is shown in Figure 2. The information on each motorcycle is given in App. I.

2. DATA ANALYSIS

2.1 Model I – Wheelbase reduction

In this model the pre-impact speed of the motorcycle is correlated with the wheelbase reduction. This model is the earliest model, proposed by Severy. The wheelbase reduction data of the previous 56 tests were graphed versus the pre-impact speed as shown in Figure 3. As shown the data is scattered and does not fit a straight line since correlation factor 0.27 which indicates a poor correlation.

Figure 1: Photos of some of the motorcycle

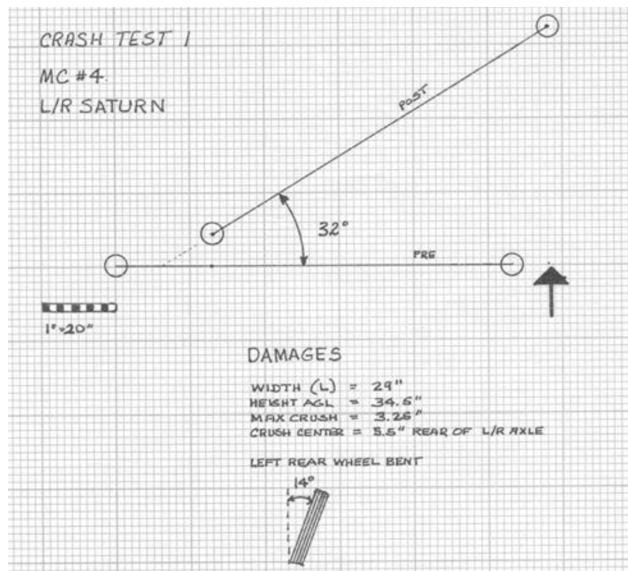

Figure 2: Data collected for each test.

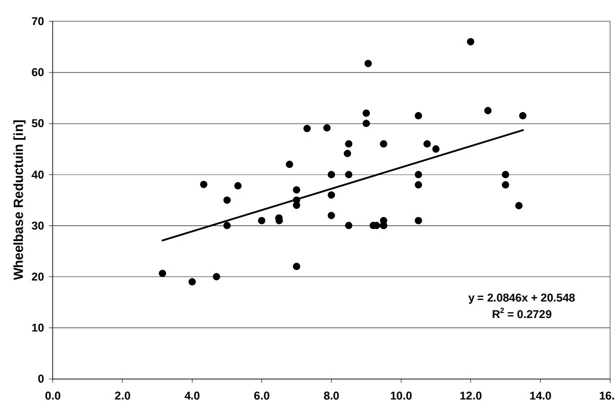

Figure 3: Results of model I.

2.2 Model II – “Total” crush

With this method the motorcycle speed is correlated with the “Total Crush” which is the some of the motorcycle’s wheelbase reduction and the maximum indentation of the vehicle’s crush. The correlation, if exists, eliminates the need of knowing the stiffness of the motorcycle structure as well as the local stiffness of the vehicle at the impact location.

However, two different cases are being considered: 1) The motorcycle strikes vehicle at a “soft” location such as a door or a fender; and 2) A “hard” point is being struck such as a pillar or within 3 inches of an axle.

For the first case the following linear relationship with a correlation factor of 0.8 was obtained (see Figure 4):

$$V = 1.43(L + C) + 10.4 \qquad (1)$$

where: V – Motorcycle impact speed (mph)

L – Motorcycle wheelbase reduction (inches)

C - Maximum indentation in the vehicle’s crush zone (inches)

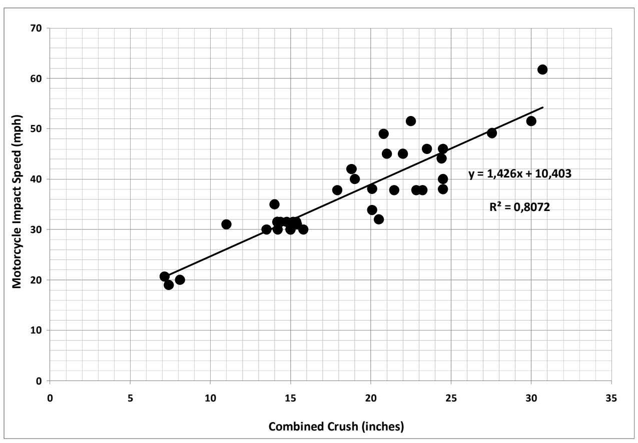

Figure 4: Motorcycle speed estimate “Soft location”

Similarly, for impacts at “hard” The following relationship with a correlation factor of 0.76 was obtained (see Figure 5):

$$V = 1.59(L + C) + 14.72 \qquad (2)$$

Using the model, pre-collision speed of the motorcycle was estimated. The estimation errors are illustrated in Figure 6 through 8 for different impact location on the car. As shown, in cases where the impact location is “hard” (pillar or axle) the largest estimation errors are approximately 30% while when the impact location is “soft” the error reach 40%. In both cases, the results are not acceptable.

The data was separated according to the location of the impact: 1) Fenders and door; 2) Pillar ±3 inches; and 3) Axle ±3 inches. The reason behind this classification is the difference in the stiffness at these locations. The results are shown in Figure 7.

As shown in Figure 7, the only “good” correlation is when the impact location is around the axle, probably because the stiffness at this point is very high for every vehicle.

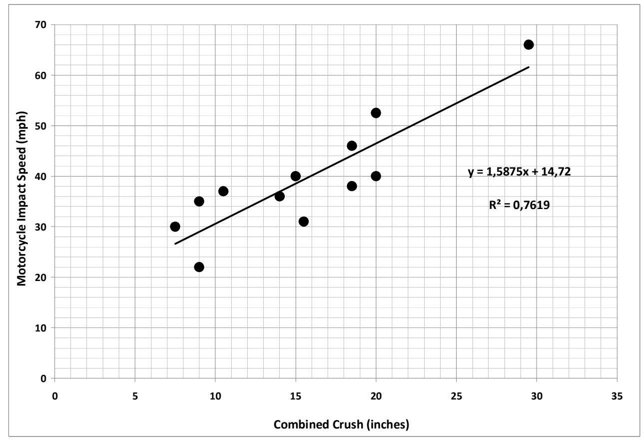

Figure 5: Motorcycle speed estimate “Hard location”

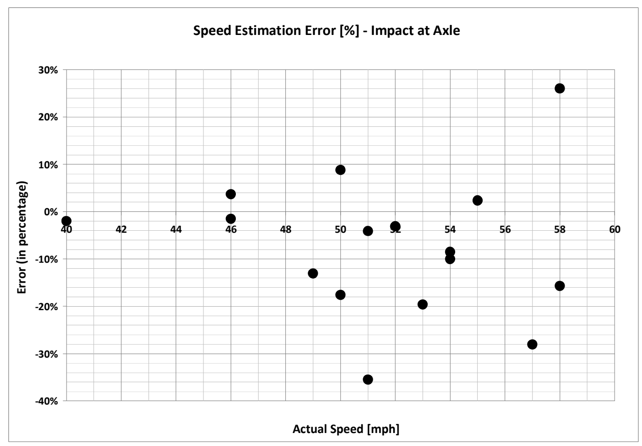

Figure 6: Motorcycle speed estimation error where impact at the axle.

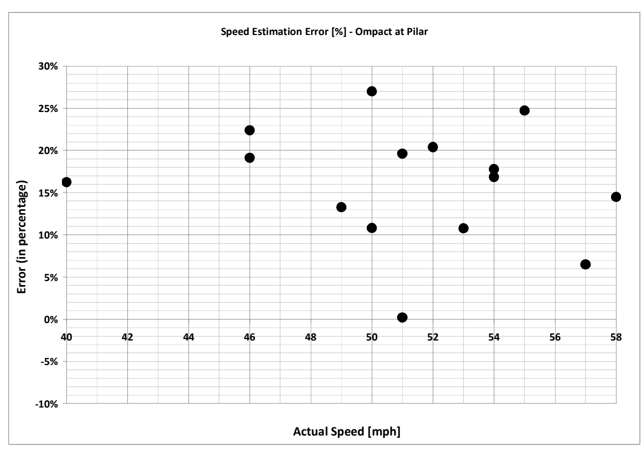

Figure 7: Motorcycle speed estimation error where impact at the pillar.

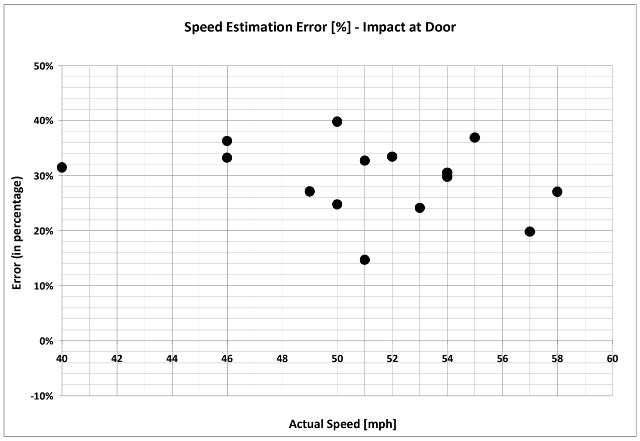

Figure 8: Motorcycle speed estimation error where impact at the door.

2.3 Model III – Conservation of linear momentum

The Law of Conservation of Momentum dictates that the total momentum just prior to two elements colliding is the same as the total momentum just after the collision. In most motorcycle collisions this basic formula must be expanded to include both motorcycle and rider post-impact velocity, since the motorcycle and rider seldom stay together following the collision. This relationship is given by:

$$(M_m + M_r)V = M_c V_c + M_m V_m + M_r V_r \tag{2}$$

where:	M_m	-	Motorcycle's mass
	M_r	-	Rider's mass
	M_c	-	Vehicle's mass
	V_c	-	Vehicle's post impact speed
	V_m	-	Motorcycle's post impact speed
	V_r	-	Rider's post impact speed

In test conditions Eq. 2 is simplified in this case since there was no rider on the bike,

$$M_m V = M_c V_c + M_m V_m \tag{3}$$

To estimate post impact speed of the motorcycle conservation of energy relationship is used:

$$V_m = \sqrt{2\mu_m g l} \tag{4}$$

Where:	g	-	Gravitational acceleration
	l	-	Motorcycle's skid marks length
	μ_m	-	Coefficient of friction between the motorcycle and the skidding surface

The same way the post impact of the vehicle can be calculated.

$$V_c = \sqrt{2\mu_c g L} \tag{5}$$

Where:	L	-	Vehicle's skid marks length
	μ_c	-	Coefficient of friction between the vehicle and the skidding surface

Using conservation of linear momentum principle, the pre-impact speed of the motorcycle can be found by:

$$V = \frac{\sqrt{2g}}{M_m}\left(M_c\sqrt{\mu_c L} + M_m\sqrt{\mu_m l}\right) \tag{6}$$

As shown in Figure 9, the use of the principle of linear conservation principle yields poor results with some cases where the estimation errors exceeding 100%. It is interesting to note that all errors are negative which means that the model overestimate the actual speed.

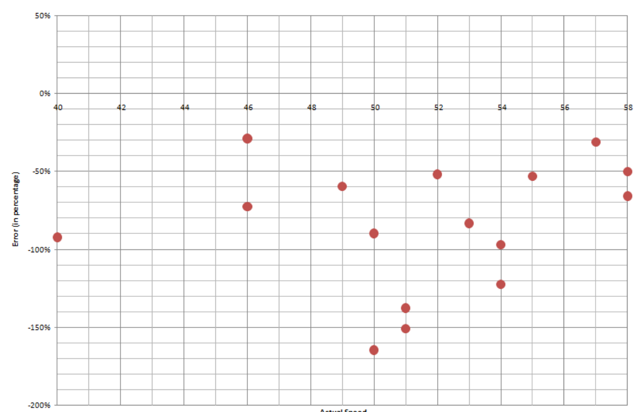

Figure 9: Estimation errors of the pre-impact motorcycle speed using linear momentum conservation.

2.5 Model IV – Conservation of Angular momentum

The McNally Rotational Momentum Method [8] utilizes vehicle information (weights, weight distributions, impact location, vehicle rotation), and scene information (post impact speed and direction of both vehicles).

The first step in the rotational analysis is to determine the total amount of torque acting through the tires/roadway interaction to slow the angular velocity of the vehicle following the collision.

In side collisions the impulse applied to the vehicle results in the struck end of the vehicle “sliding,” while the opposite end acts a pivot point. When this type of vehicular motion occurs, it is possible to calculate the torque acting on the vehicle by:

$$\tau_{tire} = M_c g W_b \mu_c \tag{7}$$

where: τ_{tire} - Torque caused by the tires sliding sideway

W_b - Vehicle’s wheelbase

The value of torque calculated above can then be used in the following formula, which calculates the rotational velocity of the vehicle.

$$\omega = \sqrt{\frac{2\tau_{tire}\theta}{I + M_c d^2}} \tag{8}$$

where: ω - Angular velocity of the vehicle

θ - Vehicle’s angle of rotation

I - Yaw moment of inertia

d - Distance of the farthest axle from the impact point to the center of gravity of the vehicle

At this point the change in the motorcycle speed, due to the impact, can be determined:

$$\Delta V_m = \frac{(I + M_c d^2)\omega}{SM_m} \tag{9}$$

where S is the length of moment arm determined by measuring the perpendicular distance from the principal direction of force to the center of mass of the vehicle.

If we know the direction of travel of the motorcycle at impact and its post-impact velocity, are know, the impact speed of the motorcycle can be determined. Figure 10 show the estimation errors of the motorcycle’s pre-impact speed. As in the previous case, the errors are large and reaching 80%. Similarly, in most cases the pre-impact speed is over estimated.

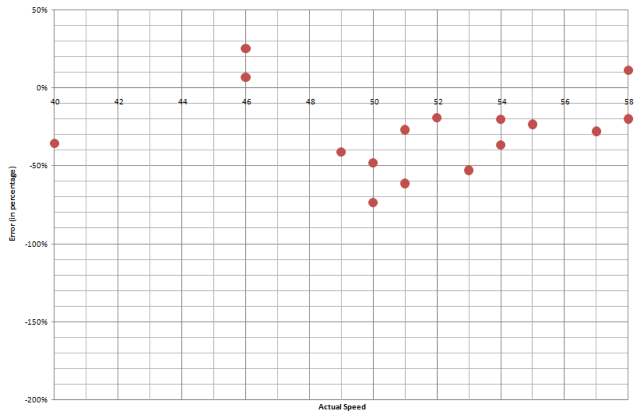

Figure 10: Estimation errors of the pre-impact motorcycle speed using angular momentum conservation.

3. CONCLUSIONS

The paper describes 5 different methods, by which the pre-impact speed of a motorcycle during a collision with the side of a vehicle, can be estimated.

While the momentum conservation methods are based on principles on mechanics, their estimate of is very poor. Out of the other 3 methods only the combined crush method produced good results.

From accident reconstruction point of you, these are encouraging results since in many cases the information available is very limited. For example, in many cases the accident site went through changes or some time passed since the accident and as a result skid marks are not available. However, at the best both vehicles are still available for inspection and the required two parameters, required for the combined crush method, can be measured.

4. REFERENCES

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APPENDIX I – Motorcycles data

CRASH TEST DATA			MOTORCYCLE DATA						
TEST #	IMPACT SPEED	MC NUMBER	YEAR	MAKE	MODEL	VIN	WEIGHT FRONT	WEIGHT REAR	WEIGHT TOTAL
1	46	4	1984	Yamaha	FJ600L	JYA49A003EA000195	179	181	360
2	46	15	1980	Suzuki	GN400	GN400506260	143	172	315
3	54	10	1986	Honda	VT1100C Shadow	1HFSC1802GA109239	242	256	498
4	54	2	1982	Yamaha	Maxim	15R002812	221	253	474
5	51	5	1997	Kawasaki	ZX600	JKAKZX4E14VB512801	219	227	446
6	50	6	1986	Suzuki	GS550ESG	JS1GN74A3G2100744	224	212	436
7	49	9	2002	Suzuki	GSX600F	JS1GN79A022101478	205	205	410
8	52	3	1985	Suzuki	GS550ESG	JS1GN74A7G2101623	193	179	372
9	50	16	1987	Yamaha	Virago XV535T	JYA2GV002HA005753	191	214	405
10	51	1	1982	Yamaha	Virago XV920J	JYA10L009CA015001	203	215	417
11	40	13	2003	Quingqi	Unknown (Scooter)	LAEAD41053B920286	58	84	144
12	53	14	1981	Suzuki	GN400X	JS1NK41A5B2108405	128	162	290
13	58	7	1981	Honda	CB900 Custom	JH2SC0405BC107905	276	310	586