# TECHNICAL NOTE

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# Modeling of Vehicular Accidents

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**ABSTRACT:** The accurate modeling of motor vehicle accidents is theoretically possible and practical. Through modeling, actual collisions can be reconstructed and reenacted numerous times and at nominal expense. Methods of presentation include: (1) multi-image stroboscopy, (2) high speed cinematography, and (3) actual demonstration of the accident in the courtroom. Two methods for modeling the actual damage to the cars are discussed. This approach to accident reconstruction should eliminate many lawsuits, because both plaintiff and defendant can observe a reenactment of a crash, and will further reduce the chances of erroneous judgment.

**KEYWORDS:** criminalistics, motor vehicle accidents, collision research, scale model tests, stroboscopes, high speed cameras, dimensional analysis

The thorough investigation of a vehicular accident usually involves the services of a variety of experts who attempt to determine what actually happened and who was at fault.

The primary investigator of an accident is a law enforcement officer, who normally arrives at the scene before the vehicles have been moved. In most cases the following information is provided by this officer in the official traffic accident report: the location of the accident; the type, make, serial number, and year of the vehicles involved; the type, width, and condition of the roadway where the accident took place; the lengths, types, and locations of all skid marks; the point of impact; the final location and orientation of each vehicle; the time of day; the directions of travel; and the estimated speeds of the vehicles.

If the officer is unable to determine who was at fault, or if his findings are contested, then a person who can be qualified as an expert witness is hired to reconstruct the accident. An investigator, with years of practical experience, will base his conclusions on as many as possible of the following items: the traffic report; all available photographs (by law enforcement agents, insurance adjusters, newspapers, and so on); depositions from, interviews with, and statements of witnesses; a visit to the scene of the accident; actual physical inspection of the damaged vehicles; itemized repair estimates; and past mechanical history and maintenance records. This investigator will relate the damage sustained at impact to the speed at impact and then using the length and type of marks left on the pavement will determine, by the use

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of a nomograph or basic equations of physics, the speed of the vehicle at the time the driver initially reacted.

An alternative type of investigator is the trained scientist or engineer who uses all of the above sources of information plus more sophisticated laws of physics and mathematics to reconstruct the accident [1]. This person is able to determine the speeds and directions of all vehicles immediately before and after the collision without having to rely on the physical damage for evidence. Theoretically, if the point of impact and the final locations of the vehicles are known facts (and these are usually available), the initial speeds and directions at impact can be calculated.

In the majority of accidents, the combined work of these two types of experienced investigators should provide a complete and accurate reconstruction, thereby enabling the court to reach an informed decision.

These methods of investigation are quite sufficient for obtaining a reconstruction that is defensible, provided that all of the necessary information is available and substantiated. However, this is not often the case. The law officer might be inexperienced and fail to properly identify and record all of the pertinent facts or might be too occupied with the injured or with controlling the traffic in a busy intersection to have time to gather sufficient data to prepare a comprehensive report. Scuff and skid marks would be difficult (if not impossible) to identify if the road surface were covered with loose gravel or with ice and snow. The drivers may be unable to supply reliable information because of alcohol, drugs, amnesia, or death. It may also be impossible to locate reliable witnesses. When the available information is incomplete or conflicting, both types of expert witnesses may be required to formulate an opinion based on their past experience, which would allow them to give more credence to some facts than to others.

In the past, when there was incomplete information (and the case warranted) an attempt was made to reconstruct the accident with full-size cars. Today this is seldom done for several reasons: it is usually difficult to obtain operable, reasonably undamaged, cars identical to those in the accident and it is very expensive (if not impossible) to hire qualified drivers; the cars can normally be used only once, necessitating that additional cars be acquired for each new trial reconstruction if the previous test proves inconclusive.

**History of Vehicular Modeling**

A practical alternative to full-scale reconstruction of accidents is the scaled modeling of collisions. In 1969, Emori and Link [2] determined by dimensional analysis that it is possible to study vehicle motion before and after impact by using scale models. Their study demonstrated that data obtained with scale models closely duplicated experimental data obtained with full-size cars in controlled accidents. This present paper is an extension of that work.

Theoretically, exact duplications of collisions of full-size cars can be obtained by using model cars. This method of reconstructing accidents is relatively inexpensive (estimated at one fourth to one third the cost of full-scale reconstructions [3]) because operable full-size cars need not be purchased, no drivers are necessary, and a large number of trials can be accomplished in a short time and the same cars can be used over and over. The effects of different speeds, different angles of approach, different points of impact between the cars, and various surface conditions can be obtained at small cost. The results of such a reconstructed accident can be presented clearly in court with multiexposure photographs, high speed movies of the model vehicles, or with an actual demonstration. The photographs, movies, or live presentation can show the velocities and directions, the relation of the cars to each other at impact, and the final resting positions and orientations. This technique is equally valuable in showing how an accident did or did not occur since a number of these items can be verified by the jury from alternative sources. These advantages should make the use of modeled collisions very important in the investigation and reconstruction of vehicular accidents.

## Dimensional Analysis

When dynamic similarity exists between the models and the full-size vehicles, data measured by using the models may be quantitatively related to the behavior of the prototypes.

Dynamic similarity is obtained when the following two conditions are fulfilled: the models used must be exactly scaled versions of the prototypes and all but one of dimensionless groups of parameters obtained by use of the Buckingham Pi theorem must be satisfied [*4*]. This last requirement dictates that the 18 physical conditions that affect the dynamics of an accident (such as distances, velocities, angles, rotations, weights, road surface conditions) be identified and expressed in terms of their fundamental quantities of length, mass (or force), and time. These 18 quantities are then mathematically arranged according to Buckingham's Pi theorem into 15 independent dimensionless groups.

An analysis of these groups determines the individual scale factors between the parameters of the model and the prototype. These are based on the size and weight of the model with respect to the prototype. The results of this procedure determine that if the scale of the model is designated as $\lambda$, then all distances will scale as $\lambda$, and time and veolcities, as the square root of $\lambda$. In addition, all angles of the rotation and all resistance coefficients will be the same for both the model and the prototype.

In the application of dimensional analysis to the modeling of collisions it is possible to satisfy simultaneously each of the 15 independent dimensionless groups by using easily obtained model sizes, weights, and speeds. Therefore, theoretically, the results from the modeling may be extrapolated to predict the exact behavior of the prototype vehicles in an actual collision.

## Practical Application of Dimensional Analysis

The results of the dimensional analysis imply that if properly weighted models were $^1/_{25}$th the size of the full-size vehicles, then every linear dimension would scale by $^1/_{25}$ (road, barriers, and so forth), all velocites by $^1/_5$, and the amount of rotations would be the same. Therefore, if the speed of the model were 9.7 km/h (6 mph) (or 48.3 km/h [30 mph] for the prototype) and if a high speed movie camera were adjusted to take pictures at five times normal viewing speed, then an accident reconstruction using models would appear in real time when shown on the screen.

A second method of presentation involves stroboscopy [5]. With this technique the accident would be reconstructed in a darkened room where a series of synchronized flashing lights were used. Before the impact the shutter of a camera would be opened and would remain open until all motion ceased. The result would be a multiexposed negative in which successive instantaneous locations of the model vehicles as a function of time would be depicted (Figs. 1 and 2). Velocities and rotations could be calculated as functions of time and distance from the point and time of impact.

It has been determined that in a real accident the coefficient of restitution (a numerical measure of the tendency of the deformed metal to rebound after impact) is nearly zero [*2,6*]. This value indicates that the maximum possible amount of kinetic energy is expended in the permanent deformation of the metal. This same characteristic behavior must be incorporated into whatever models are used. This topic is discussed later in this paper.

The center of gravity must be placed correctly. The fore, aft, and sideward location of the center of gravity can be determined by weighing each tire separately and using the ap-

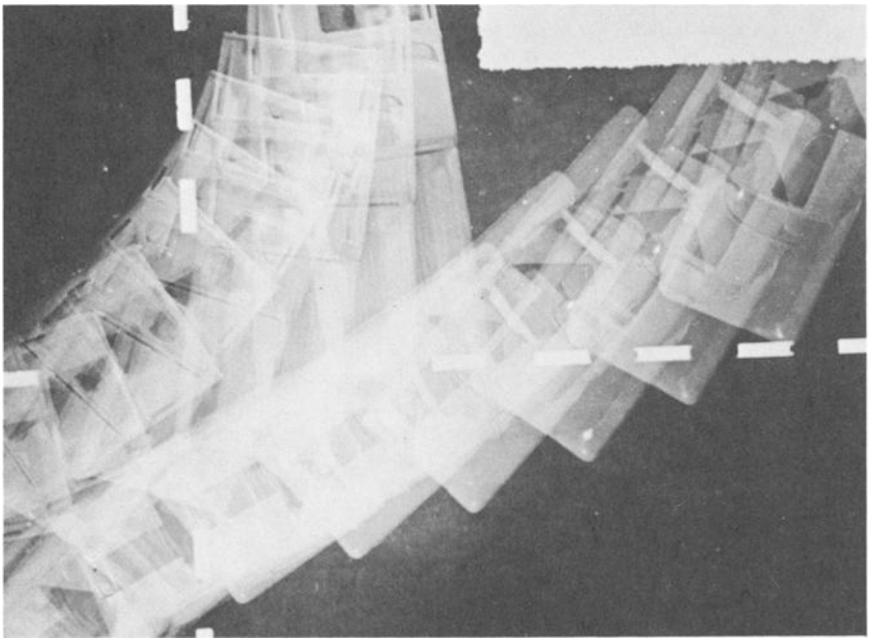


FIG. 1—*A "Strobotac" is used to capture the motion of two vehicles following a sideswipe collision.*

FIG. 2—*A high speed broadside collision showing the motion of the two vehicles at equal time intervals.*

propriate formulas. The vertical location of the center of gravity may be determined exactly by having a wrecker balance the car on its two side wheels; however, for less accurate work a "rule of thumb" locates it at one third the height of the car.

The moment of inertia of actual cars has been experimentally determined and several semiempirical equations are available for this calculation based on the overall dimensions and the weight of the vehicle [*7,8*]. The simplest way to obtain the moment of inertia of a model is to suspend the model and time its frequency of torsional vibration.

## Description of the Experimental Setup

### *Physical Layout*

Depending on the sophistication required, the layout can vary from a correctly scaled two-dimensional overhead view of the roadways painted on a 1.2- by 1.2-m (4- by 4-ft) sheet of plywood (Fig. 3) to an elaborate three-dimensional portrayal of the roadways and adjoining terrain (Fig. 4). It is possible to simulate accurately any road surface including glazed ice.

### *Model Vehicles*

A scale of 1 to 25 is recommended because of the enormous number of excellent plastic models available, including foreign cars, American cars, 18-wheel tractors and trailers, wreckers, sport cars, vans, and pickups. To prepare the models the original plastic undercarriage of the model is replaced with a brass frame constructed of 6.35-mm (0.25-in.) square brass tubing. This frame supports a heavy-duty DC motor, the drive shaft, and the axles. The model vehicles are then carefully weighted so that their weights and centers of

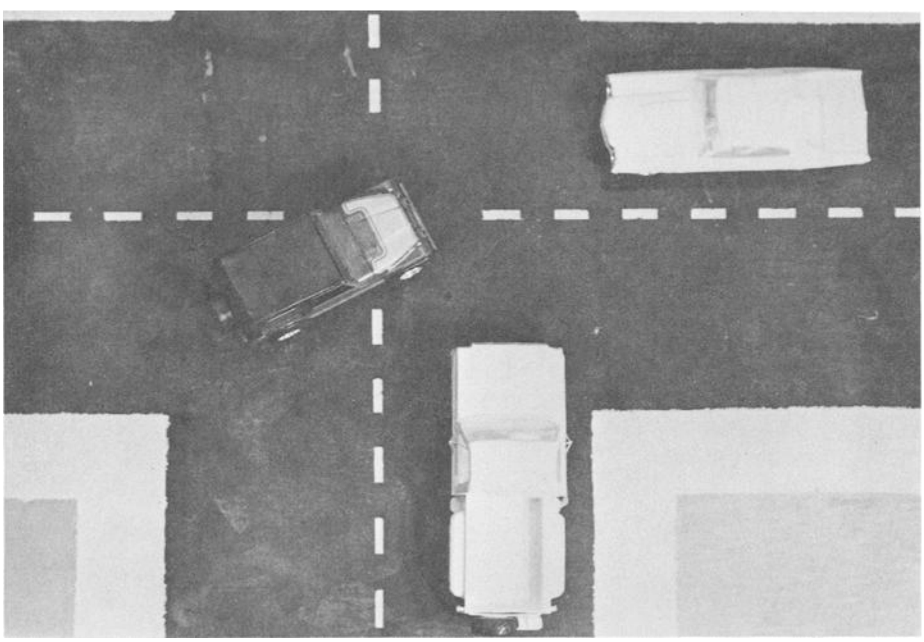

FIG. 3—*A pickup truck, a full-sized car, and a four-wheel-drive vehicle are shown at a 1/25th scale two-dimensional intersection. For reference, the spacing of the centerline markings is 25 mm (1 in.).*

gravity are proportional to those of the actual vehicles involved in the accident. In addition, the weights are distributed such that the moment of inertia of each vehicle is properly scaled.

There are various methods that can be used to satisfy the plasticity requirement. Emori and Link [2] used a paper honeycomb attached to the points of impact to provide crushable contact surfaces. Another possibility is to attach a layer of light plastic foam at the points of contact. These procedures are applicable when duplication of the actual damage is not of prime importance.

We experimented with various techniques to duplicate the actual damage incurred by full-size vehicles. Panels from plastic bodies of the models were removed and replaced by the proper number of laminated sheets of aluminum foil. The aluminum foil was formed directly over the plastic panels and provided an excellent duplicate. We also used the plastic vehicle bodies as patterns for casting duplicates out of light foam plastic. These foam bodies were then weighted and mounted on the motorized metal frames; they satisfy the requirements of essentially zero rebound of the surface. Both the foil and the foam retain the incurred deformation. By adjusting the density of the foam and the rigidity of the foil, it is possible to approximate the damage incurred by the full-size vehicles.

### *Instrumentation and Propulsion*

Each vehicle was guided to the point of impact along a raised rail that also served as the conductor for the electrical power. Each vehicle could be controlled independently and its velocity recorded immediately before impact as a function of the time required to pass between two electronic sensors. At the time of impact the models were entirely free of the rail and all external constraints. Several models were modified so that the wheels would turn a prescribed amount to the left or right after leaving the rail. This ability to turn would be necessary in a sideswipe type of accident or when a sudden turning would cause a car to flip

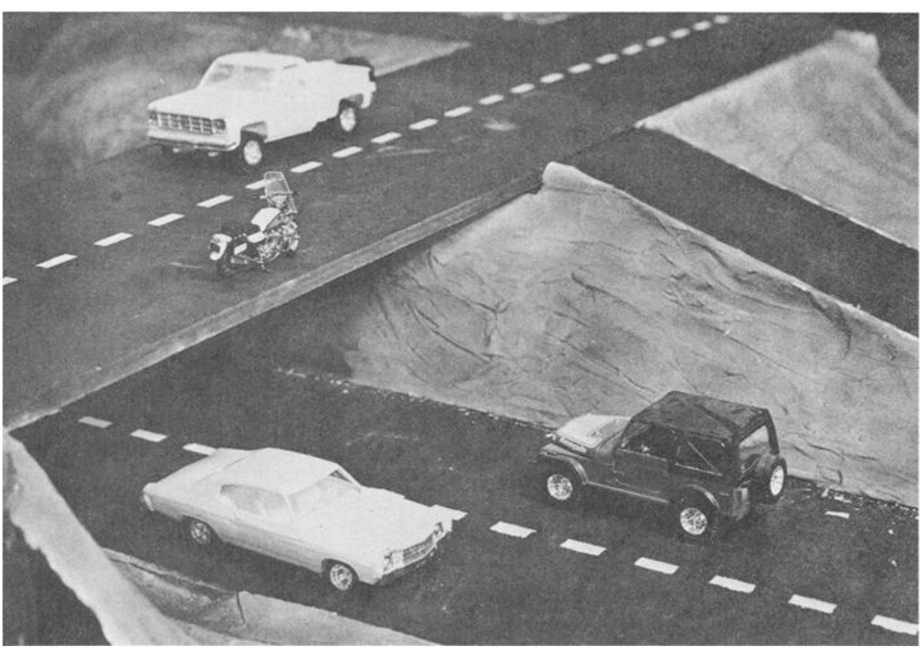

FIG. 4—*The same vehicles as in Fig. 3 plus a* $^1/25$*th scale motorcycle are shown in a three-dimensional setting.*

over. In addition, wheel lockup (or any degree of braking) can be simulated by having correctly tensioned flat springs engage the axles when the vehicle leaves the rail.

## Conclusions

It has been shown that it is both theoretically possible and practical to model "real world" highway accidents to obtain velocities and directions of travel at the moment of impact.

Two methods of modeling the actual damage to the cars have been presented. Multi-image photographs or motion pictures taken with a high-speed camera visually recreate what actually occurred at the scene of the accident. This technique allows for the reconstruction and reenactment of the actual collision to be repeated numerous times and at nominal expense. We believe that, at the present time, careful modeling of vehicular accidents is superior to all analytical formulations and to the developing art of reconstruction with computer graphics. This approach to accident reconstruction should eliminate many lawsuits, because both plaintiff and defendant can observe a reenactment of a crash, and will reduce the chances of erroneous judgment.

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