Fundamental Relationship for Roadway Safety: Model for Global Comparisons

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A fundamental relationship to explain road accidents in developed and developing countries is proposed. The relationship relies on the interaction of traffic hazard measured as deaths per vehicle, personal hazard as deaths per person, and motorization as vehicles per person. The model is a generalization derived from work by other researchers to explain world accident rates. The model hypothesis is discussed that in the early stages of motorization personal hazard has a small value while the traffic hazard measure will be large. The other extreme is a completely motorized country in which a fairly high but decreasing traffic hazard measure exists and the personal hazard is a low and decreasing value. Between these two extremes, the relationship has a maximum value of population-based deaths as measured by deaths per 100,000 people. The change between the two extremes is due in part to the better engineering of vehicles and roads and greater understanding of the system by the road users. Data from Canada (1910–1940), the United States (1906–1991), and the United Kingdom (1905–1990) are compared with those of India (1961–1985), China (1985), and other countries (1980–1985). These data fit the proposed relationship surprisingly well, and deviations from the U.S. data are fairly easily explained. The model allows the future maximum road fatalities to be forecast for developing countries.

Roughly 6 million North Americans were injured in motor vehicle accidents during 1991, and of these some 50,000 were killed. If the rate of growth in fatalities that existed before 1970 had continued, there would have been an additional 40,000 deaths in 1991.

The downturn of the number of fatalities in most Western countries during the early 1970s has been noted by many researchers (*1,2*). Smeed proposed the earliest popular accident fatality global model (*3*). Another relationship was suggested by Trinca et al. (*2*) and an education-based model was presented by Koonstra (*4*). The work reported here combines the ideas of all of these authors into a more generalized model to estimate motor vehicle accidents.

The severity of traffic accidents in a country is a reflection of the country's economic situation as well as cultural background and government policies. Partyka and Boehly (*5*) have an excellent discussion of the vehicle factors influencing road safety. The complexity of including traffic into the system of human-vehicle-road-environmental regulations and variables such as culture into a simple model is almost impossible. The data suggest the existence of a simple global model relating deaths, population, and vehicle ownership.

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EARLY MODELS

Smeed's motor vehicle fatality model used fatalities per vehicle [F/V] and vehicles per person [V/p] in the following equation:

$$\frac{F}{V} = 0.003 \left[\frac{V}{p}\right]^{-2/3} \tag{1}$$

This model was extended by Broughton (*6*) to include time. He concluded that each country should have its own model. The same model formulation was applied to Iraq (*7*) to estimate all motor vehicle accidents and collision accidents. In this study a simple linear relationship between fatalities and vehicles was found.

The Trinca et al. (*2*) road safety relationship for any country used the variables traffic safety, personal safety, and motorization such that

$$P = T \times M \tag{2}$$

where

- P = personal safety measured by number of deaths per 100,000 people,
- T = traffic safety measured as number of deaths per 10,000 motor vehicles, and
- M = motorization measured as number of registered motor vehicles per 1,000 people.

Their study pointed out that there is a relationship between these variables and the stage of a country's motorized transport.

Koornstra (*4*) states, "The history of safety measures give no particular explanation for the marked fatality decrease after the beginning or mid-seventies." He proposed an industrial-based learning model that combined distance driving (D) and fatality rate per unit distance driven (F/D) to estimate total fatalities (F). In equation form it is

$$F = D \times \frac{F}{D} \tag{3}$$

This model is conceptualized as a risk-adaptation model that is based on individual risk being dynamically adaptive within the traffic system.

POPULATION, VEHICLES, AND FATALITIES

Three countries that have reliable and continuous data on population and vehicle fatalities over the last century are Canada, the United Kingdom, and the United States (*8,9*). The basic road

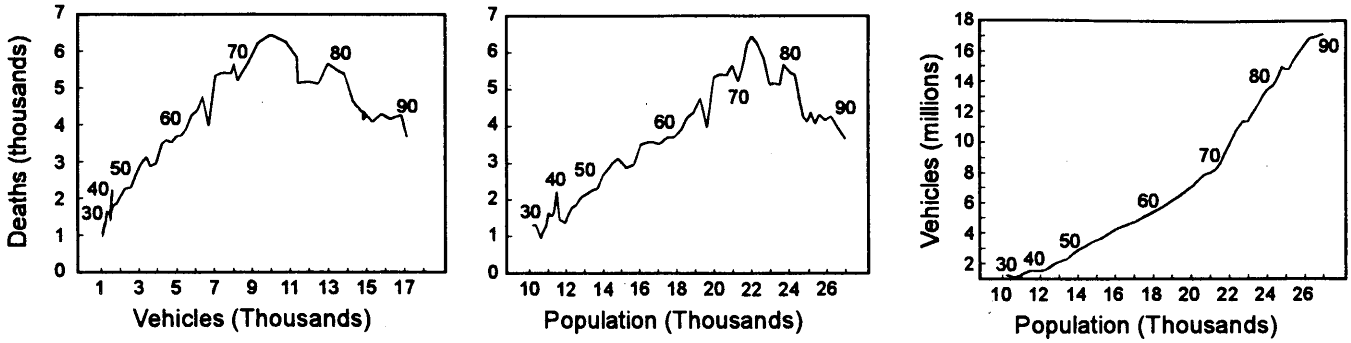

FIGURE 1 **Canada road safety record, 1910 to 1990.**

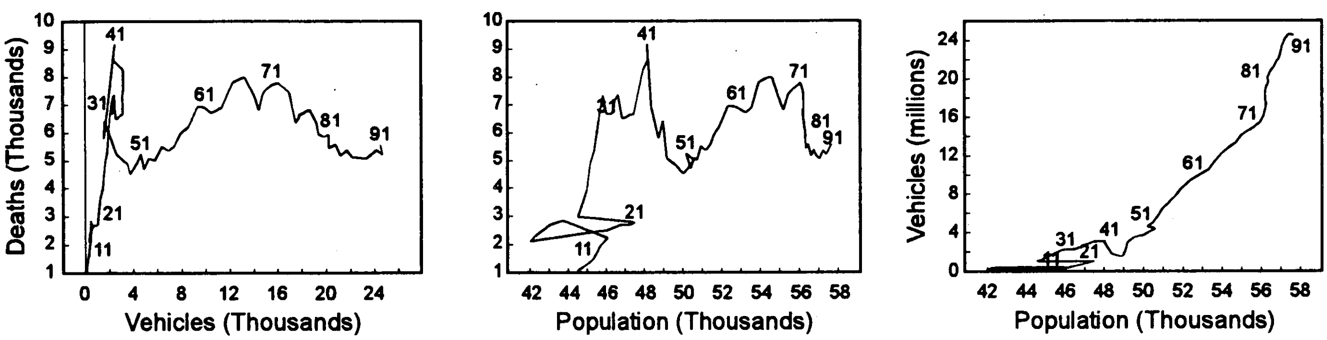

FIGURE 2 **United Kingdom safety record, 1905 to 1990.**

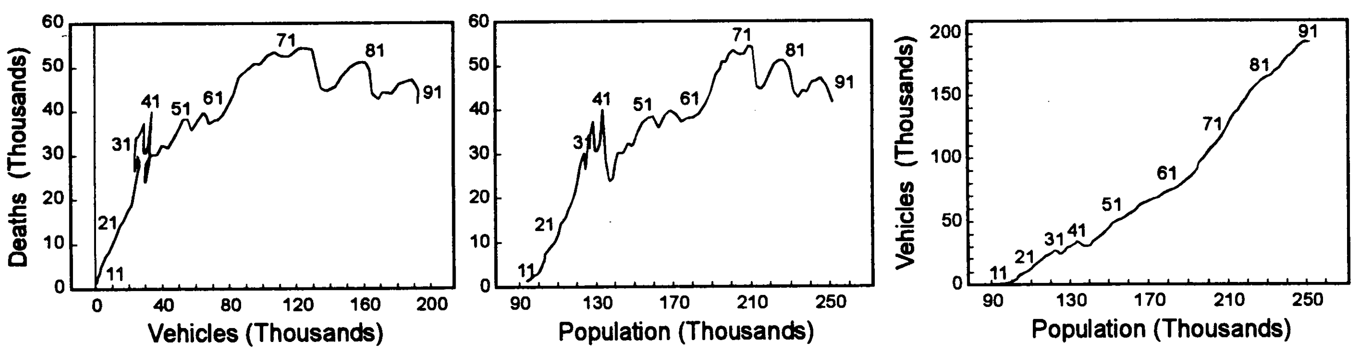

FIGURE 3 **U.S. road safety record, 1905 to 1990.**

safety data for each country are shown in Figures 1 through 3; data are given for number of deaths versus number of vehicles, number of deaths versus population, and number of vehicles per population. In all three cases when deaths and vehicles were compared, there was at first a rapid increase in the number of deaths, which peaked in the late 1960s or early 1970s and then declined. Each of the three countries had unique relationships within these general trends. The Great Depression of the 1930s and the World War II caused irregularities in the U.K. and U.S. data. Similar observations were reported for Germany and Japan (*4*) and for California, Michigan, and Ontario (*3*).

These data suggest that a fundamental model may exist to forecast the motor vehicle fatalities in any country. The general form of the model is given in Figure 4 using only the fatalities-vehicle plane. The general concept of what may be occurring follows an

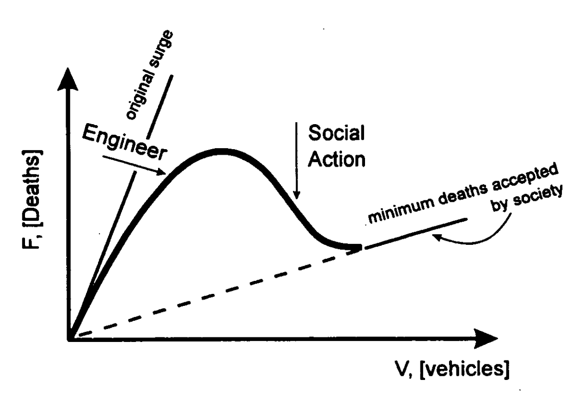

FIGURE 4 **Motor vehicle fatalities and registered vehicles.**

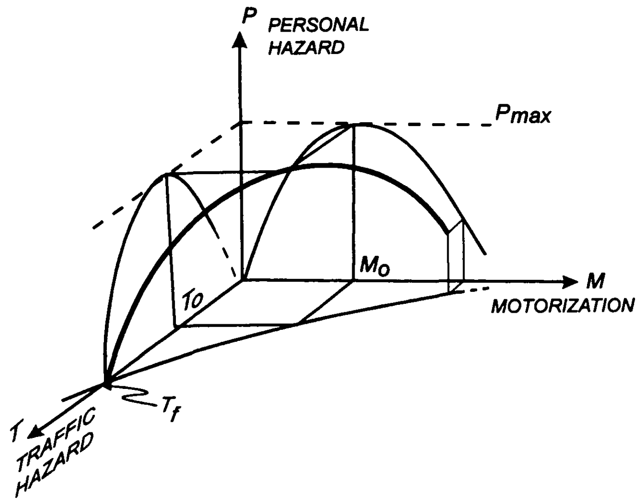

FIGURE 5 Fundamental relationship of road safety.

industrial component failure model not too different from that suggested by Koornstra (*4*). When the automobile is first introduced the population has little knowledge of how such a vehicle should be integrated into the system. Great Britain's "red flag" law is an example.

The rate of fatalities per vehicle decreases after the initial surge. Many factors may be at work but the most important is probably an increased understanding of the driver-vehicle-road-regulation system. During this phase many organizations such as the American Automobile Association, highway departments, AASHTO, and the Institute of Transportation Engineers emerged in the United States to improve conditions. The combined efforts of all these agencies do make the system safer. The third phase occurred in the late 1960s to early 1970s with strong public demand for a safer system. The social forces that brought this about may be found in the political rhetoric of the day. Countries such as Canada instituted the Road Safety Directorate within Transport Canada, giving it the mandate to write rules and regulations to reduce the coverage on the nation's roads. The result was a vastly improved automobile and a renewed effort to make the roadside more forgiving. The final phases have yet to be implemented but it is speculated that there is some lower fatality limit that represents a willingness to pay for safety or some random lower limit, or both.

FUNDAMENTAL MODEL OF ROAD SAFETY

The fundamental model of road safety proposed by Navin (*10,11*) is shown in Figure 5. The model uses fatalities as the basic safety measure and, following Trinca et al. (*2*), uses vehicles and populations as the exposure measures. This model on the *T-M* plane is similar to that proposed by Smeed (*1*), except that the hyperbolic function has been changed to an exponential function that pierces the *T*-axis as a point T_f. The value of T_f is the fatality rate when motor vehicles are introduced. The equation for traffic hazard (T) as a function of motorization (M) is

$$T = T_f e^{-M/M_o} \tag{4}$$

where M_o is the value of motorization at maximum personal hazard (P_{max}). From Equation 2, the estimate of personal hazard (P) is

$$P = MT_f e^{-M/M_o} \tag{5}$$

This model uses hazard rather than safety in the definitions. Equation 5 is similar to that developed by Underwood (*12*) for motor vehicle traffic flow. The coordinates of maximum personal hazard are given by

$$T_o = \frac{T_f}{e} \tag{6}$$

and

$$P_{max} = M_o \frac{T_f}{e} \tag{7}$$

The next question is, How well does this fit the data? First, the data of Figure 1 through 3 are transformed to the rate values given in Figures 6 through 8. The high spikes in the fatality rates of 1940 to 1945 are ignored. A very approximate set of values representing the motorization and population trends produced the results in Table 1.

The method may be applied to other road-related incidents such as pedestrian fatalities or injuries. Pedestrian fatalities provide an interesting example of a process that has two peaks. In all three countries there was a peak number of pedestrian deaths in the late 1930s and another in the beginning of the 1970s. In the case of Canada the peak was higher than in the United Kingdom and the United States.

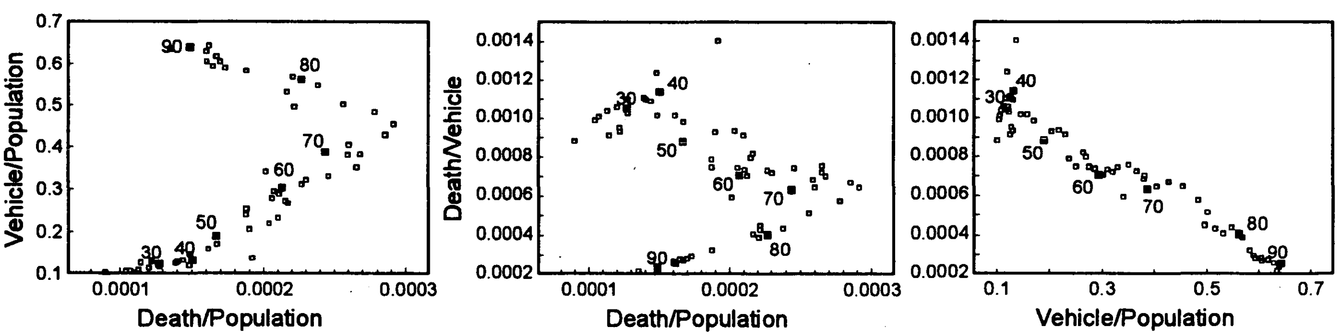

FIGURE 6 Data for fundamental relationship of road safety, Canada.

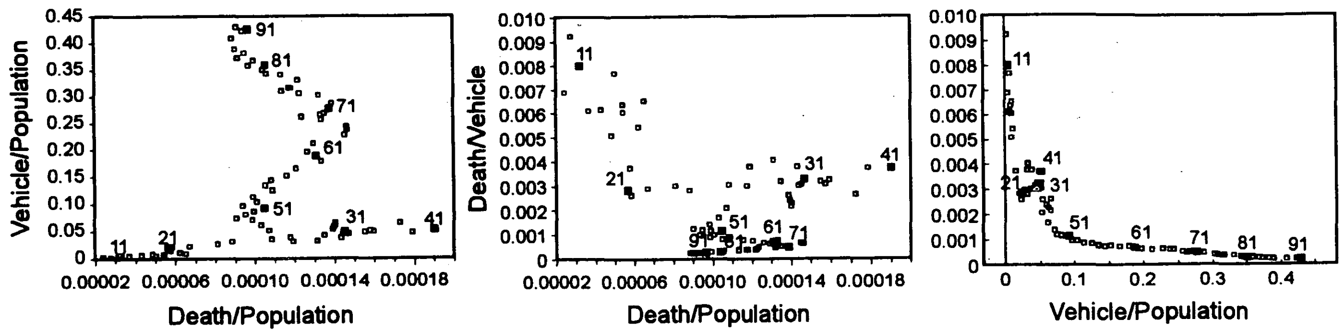

FIGURE 7 Data for fundamental relationship of road safety, United Kingdom.

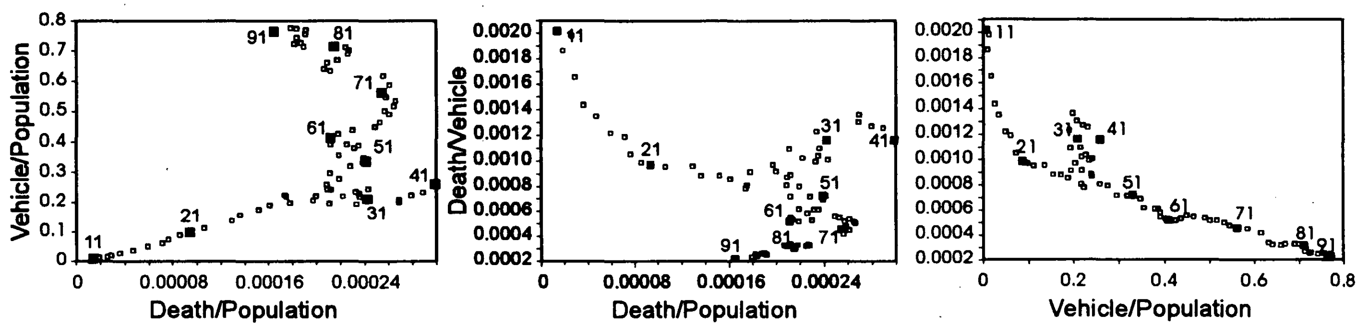

FIGURE 8 Data for fundamental relationship of road safety, United States.

TABLE 1 Equations To Estimate Traffic and Personal Hazard in Canada, United Kingdom, and United States

	Canada	U.K.	U.S.A.
T, Traffic Hazard	$0.0017\ e^{-\frac{M}{0.473}}$	$0.008\ e^{-\frac{M}{0.0645}}$	$0.002\ e^{-\frac{M}{0.427}}$
P, Personal Hazard	$0.0017\ Me^{-\frac{M}{0.473}}$	$0.008\ Me^{-\frac{M}{0.0645}}$	$0.002\ Me^{-\frac{M}{0.427}}$
P_{max}			
Estimated	0.0030	0.0019	0.0029
Observed	0.0030	0.0019	0.0029

Total motor vehicle injuries are more interesting simply because of their large number. Hauer (*3*) has injury data for a number of jurisdictions in North America and the United Kingdom. Analyses indicate that there is a negative exponential relationship between the ratio of fatalities to injury accidents and time. The approximate relationship for Canada is

$$R = 0.015 + 0.036e^{-0.05(y-1970)} \qquad (8)$$

where R is the ratio of fatalities to injury accidents and y is the calendar year starting in 1970. This equation assumes that injury accidents will reduce to some stable relationship with fatalities. The injury data plotted against time for Canada, the United Kingdom, and the United States indicates that the rate of increase has reduced or even stopped. More detailed information is needed to confidently decide whether a peak in the injury accident rate is indeed occurring.

IMPLICATION OF MODEL FOR DEVELOPING COUNTRIES

Countries in the early stages of motorization have an underdeveloped and dangerous road network. Increasing motorization increases the rate of personal hazard measured as deaths per person. This, combined with the commonly large population density of many developing countries, means that more deaths are to be expected, so the traffic hazard increases. Once the motorization rate reaches a certain critical level, the population-based death rate peaks and starts to decline.

Some developed countries have reached an advanced phase of traffic hazard, and even the population-based death rate has started to drop. This drop may have resulted from a slower increase in the motorization rate with a much reduced traffic hazard rate.

The proposed model of roadway safety can have as the dependent variable either the stage of development, or time, or both. The model is dynamic; that is, there is both an economic force and a time-dependent force that somehow makes the resulting accident rate change.

The model may be used to eliminate improvements in the safety level of a country's traffic system (see Figure 7). Observing a country's data trend, one sees how the country's position in this model changes as its motorization progressed. The U.S. and Indian data trends (*13*) are examples of how rates of roadway safety have changed over time. The U.S. data have reached the position in the *P, T, M* space at a highly motorized stage, whereas India has been moving its data upward along the cluster. Data for China (*14*) show that in 1985 the country was at the early motorizing stage and needed to endure further accident rate increases as its motorization level keeps growing.

Using the average of the global data from Figure 9, it is possible to estimate China's traffic hazard as

$$T = 0.001e^{-\frac{M}{0.0480}} \qquad (9)$$

$$P = 0.01\ Me^{-\frac{M}{0.0408}} \qquad (10)$$

$$P_{\max} = 0.00015 \qquad (11)$$

These equations imply that for a country such as China, at the peak fatality rate, about 180,000 will die annually. This figure is lower than that expected if North American rates were applied. And if the ratio of injury accidents to fatalities is similar to that in the west, then there will be about 3.6 million injury accidents. This should occur when there are roughly 0.04 motor vehicles per capita—a tenfold increase from the current level of 0.004 motor vehicles per capita. Qi (*15*) estimated the relationship between traffic hazard and motorization as

$$T = 3{,}980{,}000\ (M \times 1{,}000)^{-0.76} \qquad (12)$$

Qi's equation yields similar results to those of Equation 9.

The dynamic nature of the model implies that the relative road safety of a country is always changing. Some countries may change more than others. Whether they get better or worse depends in a large part on their stage of development and the policies that the country implements.

The model does hold out the prospect that road accident rates in more and more countries will tend to move toward those of highly motorized countries. Eventually, the scattered data may be concentrated into the end point of the model for all countries. The low vehicle-based death rate and a very low rate of population-based death rate should then prevail. The minimum population-based death rate indicates that society always will be adversely affected by the mobility derived from motorization.

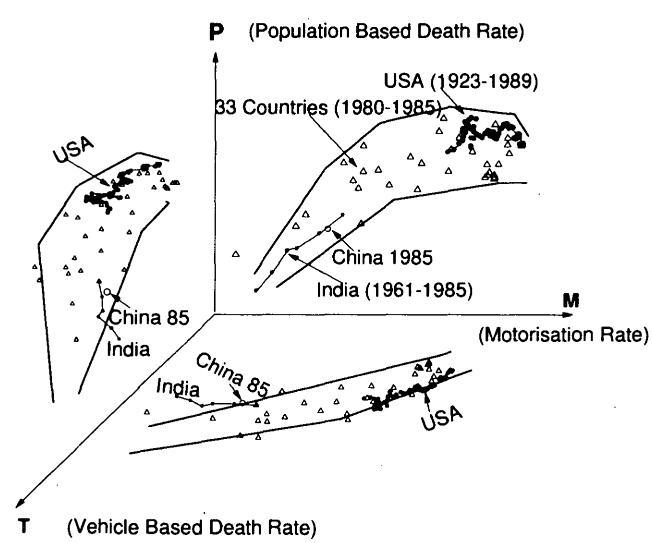

FIGURE 9 Traffic and population hazard by motorization.

IMPLICATION FOR ROAD SAFETY POLICY

The developing countries of today have more road safety advantages than the countries that pioneered the use of motor vehicles. During the early years of motor vehicle use, knowledge, and technology on how to design and build cars and roads were limited. The management of roadway operating systems such as traffic signals, signs, and markings and other traffic regulations, as well as emergency medical response systems, were limited. This knowledge and technology is available to today's developing countries; however, the knowledge may not be used. Technology transfer to developing countries in the early stage of motorization is extremely important to them and will no doubt alter the calibration parameters of the proposed model but not the shape of the fundamental relationship.

Currently in developing countries, the knowledge of the driver-vehicle-road-environment system has reached a higher level than that in Canada, the United Kingdom, and the United States at a similar state of motorization. A complete data collection system on roadway accident statistics enables better knowledge of safety-related issues and the corresponding countermeasures. For example, seat belt use has saved many involved in collisions. Restriction of drinking and driving is another example available to developing countries.

One of the similarities between the automobile's pioneer days and today's developing countries may be the large speed difference of the mixed vehicle stream on the roadways. This difference may have originated because of the lack of special roads in the early years of the pioneer countries and in developing countries of today because the budgets to finance the work were limited. Therefore, there is a high opportunity for accidents because a high risk is caused by the large speed differences. The result is that today's developing countries have large vehicle-based deaths (*T*) but small population-based deaths (*P*) because of a low motorization (*M*) level.

These similarities and differences between present and past and early and later stages of development are reflected by the low vehicle-based death ratios (*T*) but high population-based death ratios (*P*) that exist in developed countries today and very high *T* but low *P* that appear to hold true of countries at the early stage of road development. However, there seems to be too big a gap between today's developing and developed countries. Developing countries may have to go through the period of the ever-increasing population-based death rate before the trends turn down. Exactly how knowledge and technology can be used to more rapidly turn this around is not known.

In general, the world is relying more and more on road-based motorized transportation, as indicated by the high level of motorization in developed countries and the large number of overly used vehicles in developing countries. Therefore, the increasing potential of accidents and traffic hazards in the world should be closely monitored.

The model proposed in this report helps to illustrate how traffic hazard (*T*), population hazard (*P*), and motorization (*M*) may be related to stages of a country's development. There is nothing inherent in the model that says a country must go through these stages. In fact, the model does nothing more than report on the observed data for developed countries and assumes the same will apply to developing countries.

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