ADVANCES IN TRANSPORTATION STUDIES
An International Journal

Editor in Chief
Carlo Benedetto

Section A & B

Vol. IV • November 2004

Contents

Section A

Section B

ARACNE

ADVANCES IN TRANSPORTATION STUDIES

An International Journal

Section A

A new effective approach to accidents prediction to improve roads' design and rehabilitation

A. Benedetto C. Benedetto M.R. De Blasiis

Department of Sciences of Civil Engineering, University of Roma Tre, Rome, Italy
CRISS Inter-Universities Research Centre for Road Safety
e-mail: benedet@uniroma3.it

Abstract

This paper focuses on the studies and activities in the field of road safety and accident prediction carried out by the research group of the Department of Sciences of Civil Engineering Section Road Infrastructures. The group has been working on this topic since the eighties but only at the beginning of nineties the research activities reached meaningful results The new assumption formulated from the first investigations and demonstrated by the experimental studies declined the following criterion: traffic safety does not only involve kinetic and dynamical problems under the domain of road and mechanical engineering but also a multidisciplinary approach on the basis of the following assumptions: (1) traffic flow and mobility motivations influence risk thresholds and driving behaviours, (2) variability of environmental conditions affects safety standards, (3) human factors, perception reaction mechanism, decision making processes impact on driving manoeuvres and finally on safety. Traditional approaches have many points of weakness connected to the inadequacy of the accident database and to the low reliability of statistical methods for the diagnosis of the cause. Techniques based on artificial intelligence have been investigated. Neural networks are advanced mathematical models showing real and promising results, but their applicability is not easy and absolutely not efficient. Hazard analysis approach has given important, very applicable and reliable results.

Keywords – road safety, neural networks, accident prediction, safety standard, driving simulation, human factors, road safety performance

1. Introduction

It has been argued that the social cost related to the road accidents is actually considered one of the most crucial problems of the industrialized countries and more recently of the developing countries, too. Injuries and fatalities seem to show an increasing trend all over the world.

The Member States of the European Union have recently adopted specific plans, laws and regulations (2000-2004) to invert this tendency as it has been also done overseas [i.e. 27, 28, 38, 40, 44]. Apart from the social aspect, there is even a pure economic justification [i.e. 16, 37, 48, 52] for taking measures costing up to one million euros in order to save a single life [27, 29]. In fact, according to the "political evaluation" of EU Commission (2002), the records basically show that road accidents are estimated to cost about 45 billion euros per year, consisting in 15 billion for medical care, police involvement and vehicle repairs and 30 billion in lost economic production due to fatalities or injuries (source EU Commission 2002). With 45 000 victims per years, the avoidance of a fatal accident would imply saving 1 million Euro. EU has adopted programmes, financed project and implemented specific actions for promoting road safety. EU Commission does more recently declare in COM(2003) 311 final, updating the numerical estimations: "Each year, more than 40.000 people die in the European Union (EUR-15) as a result of road accidents and 1.700.000 are injured. These accidents are the main cause of death in the under-45 age group and cause more deaths than heart disease or cancer in that group. The total cost to society has been estimated at more than €160 billion a year, which corresponds to 2% of EU GNP - an exorbitant price to pay given that relatively straightforward solutions which would be acceptable to the public are not used". In this framework the risk assessment of roads assumes a relevant importance not only from an evident social point of view, but also under a financial perspective.

Risk assessment of road infrastructures is usually based on the prediction of accident with the scope of identifying the most hazardous places, calibrating the actions for reducing the frequency of accident, designing the protection barriers or the works to reduce the severity of accident [1, 31, 32, 39, 47, 49, 50]. The main problems of accident prediction are the localization of current or future accidents and the estimation of expected frequency [13, 51].

Current or future safety performance estimates for a roadway have been developed in the past by one of four following approaches: averages from historical accident data, predictions from statistical models based on regression analysis, results of before-after studies and expert judgements made by experienced engineers [30]. Finally and more recently integrated approaches and models have been formulated and calibrated by FHWA [30] to overcome the points of weakness of these methods used one by one.

Of course historical accident data are an important indicator of safety performance of a roadway. The models are theoretically very useful to identify the most hazardous places but they give no information about the causes of accidents. So no action to increase safety can be directly programmed. In the light of this consideration some points of weakness have been enlightened. Two of them are very important. First of all the database generally uses relatively short duration sample maximum to 5 years that implies low statistical significance. The time histories are short generally for two reasons: sometimes no longer time history is available, in general traffic conditions, vehicle performance and human behaviours completely change in more than five years and data could be strongly biased. Second, because the random nature of accidents, locations with high short-term accident experience are likely to experience fewer accidents in the future even if no improvements are made. This phenomenon, known as regression to the mean, makes it difficult both to identify potential problem locations through accident surveillance and estimate the potential or actual effectiveness of improvements made at such locations.

For many years safety analysts have been applying statistical techniques to develop models that are able to predict the accident experience of roadways and intersections. Historically, most such models were developed with multiple regression analysis. Recently, researchers have begun to use Poisson and negative binomial regression analyses which are theoretically better suited to accident data based on small counts (i.e., zero or nearly zero accidents at many sites). As it happens in the previous approach, regression models are very accurate tools for predicting the expected total accident experience for a location or a class of locations, but they have not proved satisfactory in isolating the effects of individual geometric or traffic control features. The assumption of each coefficient in a regression model as representing the true effect of an incremental change in its associated roadway feature is not always reliable. It has to be noted that regression models are based on statistical correlations between roadway characteristics and accidents that do not necessarily represent cause-and-effect relationships. Furthermore, if the independent variables in the model are strongly correlated to one another, it is difficult to separate their individual effects.

Researchers from all over the world have been using before-and-after studies for many years in order to evaluate the effectiveness of highway improvements in reducing accidents. However, in literature most before-and-after studies present in the design such flaws that the study design cannot account for the effects of regression to the mean. Safety experts are generally of the opinion that a before-and-after study may provide the best method to quantify the safety effects of roadway geometric and traffic control features [33] if the potential bias caused by regression to the mean can be overcome. Finally it has been argued that expert judgment, developed through many years of experience in the highway safety field, can have an important role in decision making processes for reliable safety estimates. Experts may have difficulty in making quantitative estimates with no point of reference, but comparative judgments are usually very good and reliable. The points of weakness of all these approaches have been discussed and demonstrated many times and sometimes it has been also found that the predictions completely disagree with the observations such as in the cases where the factors usually neglected by the models have a relevant influence. The research discussed in this paper moves indeed from one of this case.

2. Background

This paper presents the studies and activities in the field of road safety and accident prediction of the research group of the Department of Sciences of Civil Engineering Section Road Infrastructures that has recently founded the Inter-Universities Research Centre for Road Safety.

The group has been working on this topic since the eighties but only at the beginning of nineties the research activities changed direction greatly by carrying out a deep revision of the traditional assumptions for safety design. Until '90 safety had been generally assured by dynamical and kinetic laws while the most critical condition had been assumed for single vehicle at maximum speed, neglecting traffic flow and its expected composition, environmental situations, but the rain, and human factors. Changing of traffic conditions and vehicles' performances in the last 15 years put in severe evidence that safety is crucially affected by traffic flow and composition as well as by external and human factors. All this suggests that the theoretical models based only on dynamical and kinetic assumptions must be up-to-dated. The cited conceptual assumption about the most critical condition failed [11] and a new theoretical framework is to be formulated, verified and applied [10]. The overall objective of the researches activities, that will be here discussed, is the validation of a new method for the systemic validation of the design of road infrastructures in relation to the real traffic conditions. In this sense the scope is thought to be reached by optimizing the road geometry in consideration of the expected human behaviors under different driving and environmental situations and by controlling the quality of design analyzing the safety standards in terms of expected accidents.

2.1. The evidence

Evidence from this study suggests that the conditions of maximum risk referring to the single vehicle at maximum speed on wet pavement is denied by observations. It can be demonstrated by:

- processing the existing accident data base,
- analyzing the safety standards accepted by designer and driver,
- verifying the probability of accident in virtual reality environment or on real scale.

2.1.1 Accident data base

Numerous wide analyses of international and national accident data base show a significant correlation between accident rate, normalized to traffic flow, and traffic flow and between normalized accident rate and traffic flow origin/destination or generally traffic flow motivation.

To prevent unsafe design this certainty can not be neglected anymore. In other words the same road project can be safe or completely unsafe if traffic flow changes. The accord to traditional dynamical or kinetic standards is not sufficient to assure the safety of a road infrastructure if the traffic conditions are different from those of the single vehicle at maximum speed on wet pavement. It has been also theoretically discussed [15, 20] that the normalized accident rate changes with the Level of Service.

The case of the Italian Motorway A1 from Rome to Milan in the sections South Florence and North Florence is a self-explaining case [21]. In this case is evident that traffic flow and composition affect greatly the accident rate. Referring to a time history of 5 years, if the specific accident rate (n°. of accident / km traffic flow) of the motorway branches external to Florence node is compared to the specific accident rate of the motorway around Florence a significant evidence emerges. The probability of accident increases strongly where the motorway works both as an urban "ring" and as a branch of long connection between North and South (figure 1). The interferences between these two different traffic flows increase at the entrances and exits (figure 2). Here the accident rate is very high. Such interferences cause frequently rear end crashes. The statistics of rear end crashes is strongly influenced by the traffic density. As traffic flow increases, specific accident rate increases (figure 3). This evidence implies that a safety design can not neglect information about traffic density and characteristics of flow.

2.1.2 Safety standard

Traditional approach to road safety assumes a wet pavement and a design value for tire/pavement friction (SN_D) lower than real friction (SN_{Rw}) in order to assure an adequate safety standard (η_D). If SN_{Rw} is the real friction coefficient on wet pavement the designer generally assumes a coefficient $SN_D = SN_{Rw} / \eta_D$ where $\eta_D > 1$ is a reduction coefficient. Of course the driver assumes his/her safety standard so that the perceived friction for driver, in the same conditions of design, is $SN_{Uw} = SN_{Rw} / \eta_U$, where $\eta_U > \eta_D$ and $SN_D > SN_{Uw}$.

If the pavement is dry this assumption can fail crucially. In fact $SN_{Ud} = SN_{Rd} / \eta_U$ where the letter "*d*" is for dry conditions. Obviously $SN_{Rd} >> SN_{Rw}$ and it is possible the following unsafe condition $SN_D < SN_{Ud}$. This last condition is unsafe for many maneuvers, here the cases of stopping distance and equilibrium of vehicle in a curve are considered.

Stopping distance

Stopping distance can be evaluated using the following equation:

$$D_{stopping} = v_0 \cdot \tau - \int_{v_0}^{0} \frac{v}{g\left[SN_{D\ long}(v) \pm \frac{i}{100}\right] + \frac{Ra(v)}{m} + r_0(v)} dv$$

where: v_0 is the initial speed, τ is the perception-reaction time, g is the gravity acceleration, i the slope in percent, $Ra(v)$ the aerodynamical force, m the mass of vehicle and $r_0(v)$ the additional resistances, *long* means longitudinal. Neglecting $Ra(v)$ and $r_0(v)$, considering i=0 the equation is:

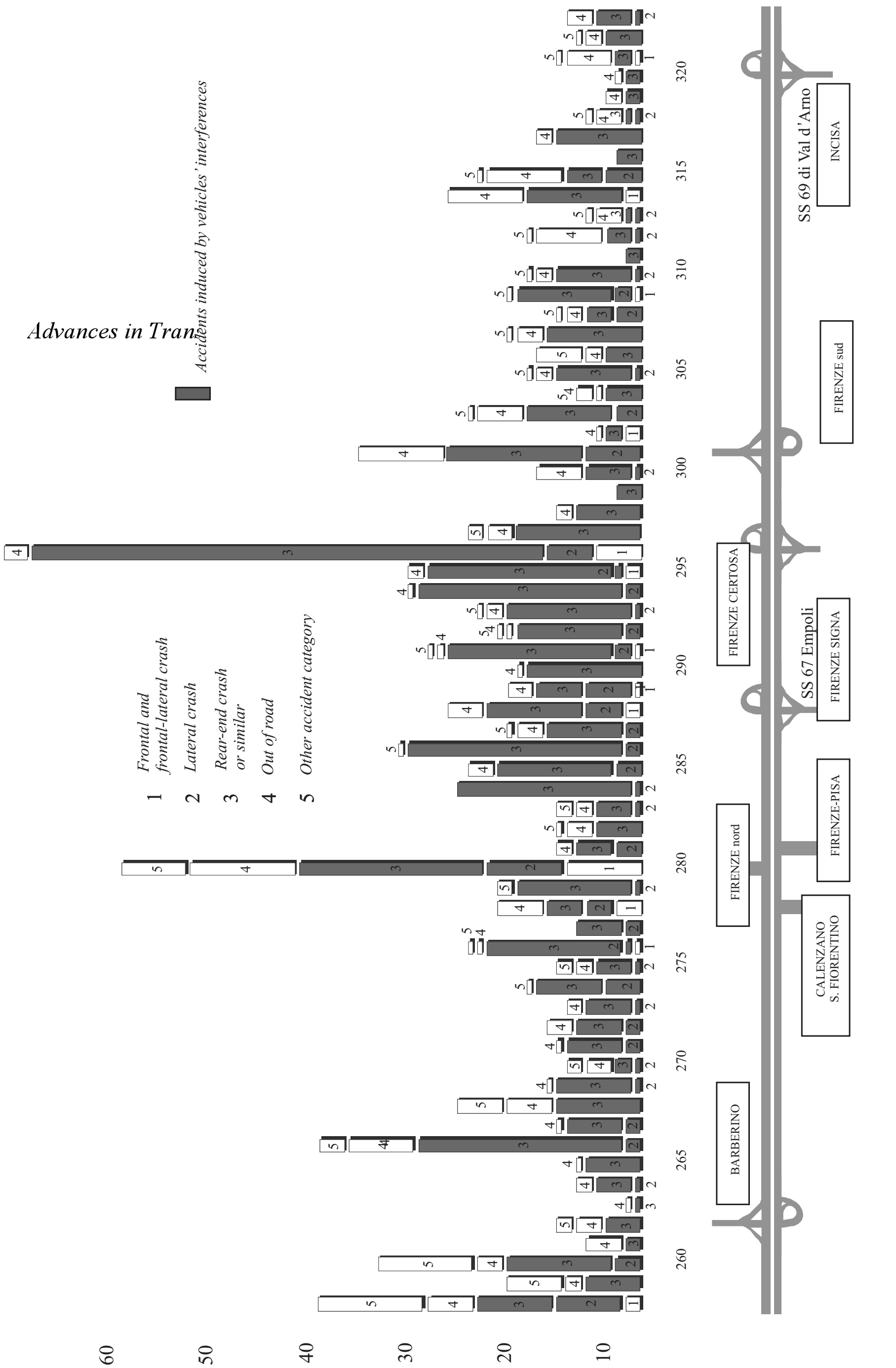

Fig. 1 – Accidents number and localization on A1 in five years

$$D_{stopping} = v_0 \cdot \tau - \int_{v_0}^{0} \frac{v}{g \cdot SN_{D\ long}(v)} dv$$

Analogously the distance needed for stopping as perceived by the driver ($PD_{stopping}$) in dry conditions is:

$$PD_{stopping} = v_0 \cdot \tau - \int_{v_0}^{0} \frac{v}{g \cdot SN_{Ud\ long}(v)} dv$$

The rate $RS = D/PD$ yields the real safety standard, if it is > 1 driving is safe, if < 1 it is unsafe.

Equilibrium in curve

The equilibrium of the vehicle in curve is assured when:

$$\frac{v^2}{R} \leq g\left[SN_{D\ long}(v) + tg(\beta)\right]$$

where: R is the radius of the curve and β the superelavation angle in curve.

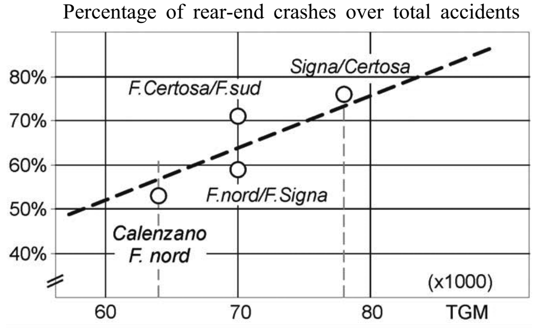

Fig. 2 – Rear end crashes over the total accidents on A1

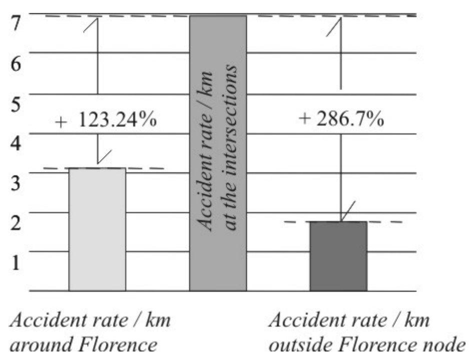

Fig. 3 – Distribution of accident localization on A1 next to Florence

Comparing the design assumption with the driver perception, the following rate yields the real safety standard:

$$RS = \frac{SN_{D\,trans}(v) + tg(\beta)}{SN_{Ud\ \ trans}(v) + tg(\beta)}$$

Concluding, if driving at the design speed in condition of dry pavement is not perceived by the drivers as a real risk threshold, the operating speeds are generally much higher than the designed one. Experimental observations confirmed that the distribution of operating speeds is usually on the average from 1.2 to 1.5 greater than the design speed [2, 9, 25]. It means that if driving of single vehicle were considered as the most critical condition in terms of safety, the human behavior in different environmental situations should be taken in the proper account. The a priori assumption that wet pavement is mostly critical is not always correct.

2.1.3 Experimental verification

Advanced technologies and new devices, such as sensors for physiological and psychological measurements, hardware and software for data processing and simulation tools, allow the researchers to:

- study the psycho-physiological stresses induced by the road and environment [i.e. 8, 13],
- analyze the single maneuvers (stopping, passing, etc.) on statistical basis [i.e. 7, 14],
- evaluate the impacts of vehicles' interferences [i.e. 6, 46],
- control the quality of road design in the expected operating conditions [i.e. 4, 13].

This upgrading of research activities is based on a multidisciplinary approach. Recently Carsten (2002) [18] has well enlightened once more the need for a multidisciplinary study of safety problems. Starting from study cases, he has noticed that "what is required is true integration between engineering and traffic psychology to create human engineering". In such a scientific framework human factors researchers, psychologists, physiologists, biomechanics experts and engineers started working together under new methodologies and using new tools. Calibration and validation processes have been developed and are under developing so as rigorous protocols for experiments have been verifying since the first steps.

In recent times four results have been found:

- numerous hypotheses assumed under traditional framework for calculation of geometrical standards are not confirmed by the real geometry of maneuvers [7, 14, 34, 41, 42],
- perception reaction mechanisms and consequently the effectiveness of each driving maneuvers depend on the legibility of visual message and on the mental workload [8, 43, 45],
- the driver adopts a risk threshold that is not constant but it is function of the stress conditions induced by traffic flow and vehicles' interferences [17, 19, 26, 35, 53],
- it is possible to formulate a judgment about the systemic quality of the project from statistical indicators [4].

2.2. New assumptions

Traffic safety does not only involve a kinetic and dynamical problem under the domain of road and mechanical engineering but also a multidisciplinary approach on the basis of the following assumptions:

- traffic flow and mobility motivations influence risk acceptable thresholds and driving behaviors,
- variability of environmental conditions affect safety standards,
- human factors, perception reaction mechanisms, decision making processes impact on driving maneuvers and finally on safety.

2.3. Final considerations

It is within this context that two considerations are needed.

First of all it is obvious that safety cannot be assured only by respecting design regulations based on mechanical hypotheses. Notwithstanding that, this is the legislative situation in many European countries and, for some aspects, it is the same also overseas. The case of Italy is particularly critical. Only in 2001 the Decree of Regulations for Roads Design was approved by the Infrastructures Ministry. The Decree up-to-dates previous technical regulations totally according to traditional approach based on a "standing alone engineering perspective".

Second, the problem is much more complex for the rehabilitation and the renewal of existing roads than for the development of new infrastructures. In fact rehabilitation works that are not validated at the scale of entire infrastructure cannot be effective but often delocalize old singularities in new sites, without increasing global safety.

The best evaluation of safety standards should predict the rate of expected accidents. But if accident is the final conclusion of a series of concomitant and consequent events under specific environmental conditions, depending on perceptions, decision making processes and reactions, traditional models are unreliable. This is the reason why the activities of our research group have been investigating new domains from 1995. Accepting that the mechanism of accident generation is very complex we have decided to avoid any in-depth investigation and we have tried to validate a "black box" model that could learn from training experience: the artificial intelligence.

3. First attempt: prediction of accident using an approach based on neural networks

The theoretical bases of the neural networks technique are widely discussed in literature [36, 54]. This mathematical technique has been applied to numerous different problems, when the cause-effect mechanisms are very complex and many data are available for statistical analysis and networks training. A perceptron network with one hidden layer has been used. It has been trained with a back propagation algorithm.

Three main principles for a reliable application of neural networks must be summarized:

- the definition of input and output must be complete and correct to assure the effectiveness of the training phase;
- the architecture of the net must be adequate respect to the specific application;
- the data base dimension for the training must be proportional to the degrees of freedom of the investigated process.

These three principles are verified when the network generalizes the input/output mechanism, that is when the net simulates correctly events that were not considered during the training.

3.1. Premises

Neural networks techniques for accident prediction can be reliable and effective only after the correct definition of the application domain in terms of input and output [22, 24]. The definition of input is difficult because all the variables that influences the generation of accident and its development are to be taken into account. At this regard four primary variables have been identified and some secondary variables belonging to the four groups are subsequently defined. Primary and secondary variables follow:

- road characteristics (road category, geometrical standards, local anomalies);
- traffic conditions (flows, composition of the flows, service levels, maximum flows);
- physical interferences (intersections, road signs, land uses);
- environmental interferences (weather, seasonal events, visual stresses, work mental load).

Each secondary variable can be splitted in elementary indicators such as radius of curve, dimension of lane, intersection type, etc.

Of course the identification of variables is the most critical phase because the training of the networks fail if one relevant variable is neglected.

The list of variables does not consider the vehicle as a possible cause of accident, because in general it is statistically not relevant.

About the output two reasons for biased data have to be considered. Some available databases take into account only severe accidents (with deaths and injuries). The accidents without severe consequences are not recorded. The development of safety equipment has so greatly reduced the consequences of accidents and that the statistics extracted from databases could sometimes be biased. As a consequence the networks manage the data difficultly. In the same way the pathologic behaviours of the drivers could bias the statistics from data, but they are not numerous and statistically not significant.

These problems can be solved through an adequate architecture of the neural networks and data filtering, but sometimes the corrected dataset can be not numerous enough to train the networks. This is a problem that generally cannot be solved.

3.2. Neural networks application

The neural networks have been applied to accident prediction in order to forecast the rate of accident and their localization, excluding the events that are not directly or indirectly caused by the road. The first problem to be solved in networks application was the filtering of accident database in order to identify casual and repetitive accidents. Casual accidents are not induced by the road and they have to be neglected in any diagnosis of pathology of the road. But when a same accident happens in a repetitive way at the same location it means reasonably that somewhat element of the road affects safety, probably not always but in specific traffic conditions [23].

Then a statistical model has been applied to weight the events according to their repetitiveness [23]. In fact if a category (i.e. frontal crash, lateral crash, etc.) of accident is more frequent than others it is probably why the road induces a wrong and unsafe behaviour. For example let us think to a very high percentage of frontal accident localized at a specific section of a road. In such a case passing sight distance could be probably inadequate or traffic conditions induce wrong human behaviour and drivers pass accepting a low risk threshold. It causes a relevant percentage of frontal accidents. The repetitiveness is sometimes independent from the road but intrinsic to the information and data. For example if we consider 4 accidents categories and the accidents on a specific homogeneous arc of the road are 5, obviously one category has at least two event, independently from road.

If the generic sequence of n accidents is $(h_1, h_2, \ldots h_n)$ and k_1 is the number of accident belonging to the category 1, k_2 the number of accident belonging to the category 2 and k_m the number of accidents belonging to the category m, the probability of the sequence $(h_1, h_2, \ldots h_n)$ is:

$$P(h_1, h_2, \ldots h_n) = (p_1)^{k1} (p_2)^{k2} \quad (p_m)^{km} = \Pi(p_i)^{ki}$$