Structural Multivariate Road Safety Modeling State-of-the-Art

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Abstracts and key words of the three parts and of the conclusion

Part I Abstract

The first part of the state-of-the art focuses on the origins of road safety modeling, covering data, early models and the public health context of model formulation and use.

Yearly tallies of road victims by severity category, typically computed nowadays from police reports, emerged over time in many countries from systematic determination by Administrations of Justice of the non-criminal nature of reported individual road crash and damage events. Such data series on retained "accidents", as available over the last 150 years (notably in France), imply very important gains in kilometric safety rates over time with the replacement of horse-drawn carriages by motor vehicles and with the spread of motor vehicles themselves.

However, multivariate statistical analyses reaching beyond two-way frequency tables are recent: aggregate national fatality rates were first modeled (as Gaussian distributions with a regression component) by Smeed in 1949, but morbidity rates were then neglected; and samples of discrete occurrences of individual accidents (of any severity) were first modeled (as Poisson distributions with a regression component) by Weber in 1970, but without concern for national population values.

These seminal single-outcome models gave rise to two streams of explanations, distinct to this day, that share a "public health" epidemiological emphasis on the establishment of multiple correlations which give rise to testable corrective policy interventions. These are still of limited value in the explanation of the simultaneous peaking of fatalities in many OECD countries in 1972-1973 (called "the Mystery of 1972-1973", hypothesized here to be occasioned by the passing of the demographic baby boom wave) and as guidance in the design of policies for the containment of road risk arising from the intrinsic dangerousness of individuals.

Part I Key Words. *Observed road victims without crime; road crimes without observed victims; discrimination and moments of random variables; unsustainable horse transport; safer motor vehicle transport; secular gains in kilometric road safety rates; aggregate national data; individual accident data; Bortkiewicz; Smeed; Weber; Gaussian; Poisson; regression component; public health knowhow; Mystery of 1972-1973 peak in road fatalities; baby boomers reaching maturity; intrinsic dangerousness of individuals.*

Part II Abstract

The second part of the state-of-the-art focuses on the development of the founders' double streams explaining single outcome indicators (probability of accidents and fatalities, respectively) by fixed form regression, as outlined in the Part 1. Following Page (1997, 2001) and others, we use as turning point of the evolution of both aggregate and discrete approaches the DRAG-1 model of 1984, itself based on aggregate data, which introduced four key innovations in principle applicable to both streams.

The DRAG approach (i) decomposed losses (victims or damages) into a product of exposure, frequency and severity terms and formulated distinct explanations for all such terms; (ii) structured the decomposed problem as a system of simultaneous equations that included not only those three levels but a fourth one designed to explain driver behavior and make it endogenous; (iii) within each of the four principal levels, took into account subcategories of severity the joint determination of which constituted a complete system of demand that brought numerous substitutions and complementarities into play; (iv) used for all specified equations flexible mathematical forms of the Box-Cox type applied to all regression variables. These forms were decisive in defining statistical correlations (signs included), upon which they themselves depended, and in justifying the initial breakdown into multiple risk dimensions by revealing the mathematical form appropriate for each level (exposure, frequency, and severity) of the decomposition.

Using these four critical dimensions, we summarize both aggregate and disaggregate model developments, classifying them notably with respect to number of risk outcome levels addressed, severity categories accounted for, mathematical form of their variables and number of classes of explanatory variables put to contribution. For aggregate models, we document evolution from early ones explaining a single damage category for one region to the latest explaining multiple damage categories for many regions, not forgetting intermediate cases. With respect to the disaggregate models, in addition to providing a classification with respect to the same four dimensions, we raise the specific problems of aggregation from individual to population values without which discrete analysis remains of limited relevance, giving disproportionate attention to the landmark by Bolduc et al. *(1993, 1994, 2012).*

Part II Key Words. *DRAG road accident model innovations; decomposition of road damages among exposure, frequency and severity dimensions or risks; endogeneity of driver behavior; Box-Cox forms and unconditional regression signs; road safety outcomes as a demand system; multivariate formulations; time horizon of adjustment; survey of aggregate model development; single-outcome, single-region models; multiple-outcome, multiple-region models; survey of discrete model development; aggregation from individual to population values.*

Part III Abstract

The third part of the state-of-the-art focuses on the future of road safety modeling and on conjectures concerning the evolution of national safety indicators. In the absence of econometric developments specific to road safety modeling, the research future must rely on pre-existing statistical procedures of econometrics applied to discrete/count and to aggregate data. In terms of contents, growing interest in the heterogeneity of road accident outcomes by category of victims could lead to treatments of this issue across research streams, say by top-down and bottom-up developments, but this speculation does not rest on extant adequate formulations of the issue of road user class and victim analysis. But understanding the time profile of aggregate national performance indicators is quite another matter.

Concerning forecasting, a key question in countries where the absolute maximum of fatalities is still to come is that of its occurrence, but the answer requires a yet missing explanation of "the mystery of 1972-1973", here hypothesized to result from the passing demographic wave (see Part 1). This ignorance affects the corresponding answer, in countries for which the maximum is long past, as to whether current performance is heading toward a minimum or toward a constant level: such a forecast can hardly be made if the maximum remains unexplained. In addition, it matters whether any envisaged asymptotic limit amounts to a natural rate combined with a random component, or includes more. It is conjectured that a regression component that would include speed, traffic density and vehicle occupancy rates could explain both the peak of 1972-1973 and the current evolution, notably of fatalities.

In the absence of a certain explanation of the Meadow/Matterhorn/Cervin peak profile of the past maximum, forecasts can only combine random terms and known explanatory factors in the notion of Conditional Expected Safety Performance, which includes that of (Conditional) Expected Maximum Insecurity (EMI) and seems preferable to Vision Zero or to alternatives based on analogs of the natural rate of unemployment. Conditional expectations do not skirt the issue of the "level of the tide" by assuming the presence of an unexplained trend level and manually changing it by shifts due to well understood specific safety measures.

Forecasts of explanatory variables require views on the political market (notably on the identity of the future median voter), on the workings of individual risk compensation, on the role of economic activity and on the chances of decoupling growth from transport demand, a weak prospect where communications appear more as gross complements than substitutes.

Part III Key Words. *Road victims by category; natural road accident rate; vision zero; Conditional Expected Road Safety Performance; expected maximum insecurity (EMI); median voter; risk compensation; uncoupling transport and the economy; transport and communications as complements; speed/traffic density/vehicle occupation rate conjecture.*

Conclusion Abstract

*The conclusion re-emphasizes the lack of recognition given to Weber's work of 1970-1971 and selects for further comment some questions left unanswered: (i) whether the way down from the Meadow/Matterhorn/Cervin-shaped peak in road fatalities around 1972-1973 leads to a plain or not in the U.S., and exactly how the **Speed/traffic density/vehicle occupancy rate Conjecture** could be tested to clarify the matter; (ii) how to distinguish, in a plain, the strata for **bottom-of-the-barrel** unresponsiveness in drivers, **uncontrollable factors** and the **randomness level** inherent to accidents. Finally, an explanation of the popularity of conditional severity models is presented.*

Conclusion Key Words. *Fatalities in the United States; the return of accident proneness.*

Part 1. National road safety performance: data, the emergence of two single-outcome modeling streams and public health

1. The emergence of national safety performance statistics

1.1. National road safety performance statistics built from police reports

In most industrialized countries, and in particular in the OECD's 30 member countries, police reports or other reports of road accidents are automatically computed into statistics on numbers of victims and categories of accident over a given time period. Government statistics cover accidents causing bodily harm (death, injury) and accidents causing material damage[1]. These statistics are published on an annual basis most of the time but some are also produced on a monthly basis. Occasionally, public policy research groups publish results relative to declared road safety performance targets (ITF/OECD/JTRC, 2008a, 2008b). A number of international institutions forecast and publish annual world figures on the expected number of road victims, killed or injured (WHO *et al.*, 1996; WHO, 1999, 2004). These statistics raise a hard question: given the 600 million cars in existence in the world today and the 1.4 million persons killed every year on roads (more than 3,000 per day), what will occur if the forecast of 3 billion cars actually becomes reality, a number envisioned in the near future?

1.2. Can one make sense of something as unpredictable as accidents?

It is proper to question the grounds on which analyses of these world tallies are undertaken by examining the underlying models used to explain aggregates and generate forecasts. Our interest in explanation require so-called "structural" models, which are generally more than simple autoregressive forecasts of time series, that seek to explain why the outcomes evolve as they do. Our interest is also often in cross-sectional data, less popular with "autoregressive activists", and naturally also in individual data, often called "discrete" even if many of the relevant variables are continuous. But, if understanding "structurally" means digging below the number itself and using something else than the thing itself to explain it, what is there to be explained by "other" factors if accidents are by definition chancy and random, rather than voluntary?

1.3. The traditional source of statistics on road accidents is the Department of Justice

It is only relatively recently that national statistics on road safety performance have come to the attention of analysts. One would assume that this interest would come from transport departments and institutions, but it actually originated in the judicial arm of government where fiscal or legal reasons require that each and every death be accounted for. In order to claim taxes at time of death, Justice departments classify deaths by cause, defined as accidental, natural or criminal, *i.e.*, make use of the categories A, B, D and E in Table 1.

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[1] Insurance companies occasionally publish information on accidents causing material damage and their frequency.

**Table 1. Accidents and crimes on the road: role of the official report
and of the individual's intent**

Case	A	B	C	D	E
Category of deed	**Accidental**	**Normal**	**Intrinsically predictable** (highly probable on average or too little uncertain)	**Self mutilation or suicide** aimed at author	**Criminal** aimed at others
Example	drowning, fall, fire	wear, sickness	repeated sexual aggressions in the past	self mutilation to obtain insurance	**[...]**
Road example	road accident	driving under the influence of medicines	driving under the influence of alcohol or narcotics	suicide, *e.g.* car driven into a train	car used as an arm
Deed or act	*Brutal external*	*Internal to the individual*			*Brutal external*
Reported occurrence	**Deed** fatal, injury or material damage		**Disposition without deed** fatal, injury or material damage	**Deed** fatal, injury or material damage	
Individual's intent and realization	*involuntary* deed, <u>*zith a report of the deed*</u>		individual state, ***voluntary or not***, assimilated to a crime <u>*zithout a reported deed*</u>	*voluntary* premeditated deed <u>*with a report of the deed*</u>	

1.4. The slow integration of safety into policy making

For a long time, well known or important texts written on or about transportation rarely referred to accidents. For example, Duclos (1759), Permanent Secretary of the *Académie Française*, in his very famous "*Essais sur les ponts et les chaussées, la voirie et les corvées*", mentions accidents only in passing, in a two-page long discussion about the cobblestones[2] of Paris claimed to be so frayed at the edges that carriage wheels wear them out fast, making the surface slippery for people to walk on when wet and dangerous for horses when dry (p.253, *op. cit*). He mentions accidents again only once in a section dealing with the banking of roads in turns: these were apparently so poorly built that they would cause accidents, thus harming both pedestrians and carriages at night (p.255, *op. cit.*).

This benign neglect of accidents was indeed the rule in the transportation policy in one of the largest countries of Europe at the time, a country where hundreds of travelers, if not more, were killed every year on the roads, crushed or struck by horses and horse-drawn carriages! Accidents and safety became integrated into policy very slowly: the concern arose first and foremost as the responsibility of Justice Departments.

1.5. What is an accident and what is a crime?

It seems that Justice has traditionally sought to differentiate between unintentional accidents and intentional ones: the emergence of category C in Table 1 is fairly recent. It refers to the criminalization of the "noted state" of a person without reference to any current related act or deed, intended or not, of that person.

Previously, our legal frameworks refused to consider as criminal physiological states (*e.g.* inebriation), or psychological states (propensity towards sexual assault), in the absence of deeds or acts. Nevertheless, since the criminalization of inebriation in the 1970s, other "states" have come to be also considered as "criminal" whether or not they were accompanied by acts. Thus, simple possession of drugs, for example, is nowadays automatically punishable notwithstanding lack of proof of intent to use or sell narcotics.

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[2] Duclos recommended that the sandstone cobblestones be changed every 20 years.

1.6. The victimless road crime: a new concept in need of a justification

Historically and from a legal standpoint, dangerous or incompetent individuals could be isolated from society, forcefully[3] if necessary. In the absence of specialized facilities to house these "intrinsically dangerous" individuals, some hospitals partially became prisons[4]. Today, some prisons have partially become hospitals for "intrinsically dangerous" asocial persons (*e.g.* repeated and proven sexual assault offenders) or high-risk individuals (*e.g.* with repeated arrests for inebriety) as defined by the Criminal Code. Today also, many of these individuals are neither hospitalized nor treated.

The lack of a clear definition of what is a crime sometimes creates paradoxical situations[5] that modeling may help to solve by formalizing the distinction between "what is expected" in a state (the first moment of a random variable) and the "variability" (meaning the variance or second moment of a random variable) of what is expected. The judicial system seems to evolve as if, on roads at the very least, discrimination (in the sense of the first moment that tells us that on average an 'inebriated' individual will kill or harm another) is preferable to inter-individual variability (that tells us that being inebriated does not guarantee that this individual will have an accident causing bodily harm, even if it has been established that inebriation does so, on average, in such cases). This occurs when, everywhere else, selective discrimination based on averages of group characteristics is denounced as being unfair to inter-individual variability.

1.7. Discrimination and moments of road accident occurrences

Discrimination means that we take decisions concerning individuals belonging to a group because we correctly expect members of the group to produce, on average, X consequences, irrespective of the fact that it is untrue of any specific individual and perhaps even untrue of all individuals in the group. For example, the average risk of road accidents per kilometer varies with the driver's age. The relation forms a U shaped curve from ages 20 to 80, with a minimum (see Figure 7.A) close to ages 40-45. This does not mean that that any given 20-25 year-old person is less safe than another from the 40-45 group, or that any mature person is safer at the wheel than a younger or an older one.

Consider the moments of random variables. We know that taking some minor tranquillizers doubles the average risk of accidents (Skegg *et al.*, 1979) and that certain drugs in particular

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[3] For example: up until the middle of the 20th Century, in the United States, a conviction for repeated sexual assaults could lead to castration.

[4] The historical origin and distinction between hospitals and prisons needs clarification. Prisons have always existed, but not hospitals. There were areas dedicated to lepers in antiquity, as there were also areas where the sick went to recuperate or to find cure: away from cities, in temples and around pools, such as Siloe's, as well as in pagan centers of pilgrimage. But the origin of the hospital proper is attributed to Saint Basil the Great who created the institutionalization of care provided by dedicated personnel: in 371, he built the first hospital (*nosokomia* in official Greek – ever since Justinian) in Caesarea. Generally called to this day a Basiliad, the institution resembled a village where friendless strangers, the sick and the poor, lepers and old people were cared for and treated. The bringing together in one location by this Great Cappadocian of organized and trained personnel dedicated to caring for others created the first institutional supply of hospital service. He also wrote the first rules on how to care for the needy, rules that gradually developed into other monastic rules giving a large part to work, such as Saint Benedict's. Hospitals or Basiliads were not prisons.

[5] In Quebec for instance, as in all jurisdictions that have adopted a Highway Code where the individual is not responsible for an accident causing bodily harm and where it is illegal to sue the driver responsible for the accident that killed a person (the "no fault" automobile insurance system), killing 10 people on the road in a year is not a punishable crime but driving after having had a bit too much to drink and killing no one is. This rule combines crimes without victims and victims without criminals.

multiply the average risk by 5 or more. But taking medication is not a criminal act. What, then, determines the moment when taking medication becomes "a tendency towards crime" or "intrinsically dangerous"? Is it the average or the standard deviation? Does the asymmetry of this probability (the third moment) play a role in the decision to label as "criminal" physiological states independently from any related actual misdeed? Or is there more than meets the eye, like some attitude towards alcohol in Puritans, or even their righteous hatred of libertines?

1.8. Criteria used to determine accidental deaths and judicial tradition

Justice departments have been compiling accidental deaths for a long time. In countries of Anglo-Saxon tradition for example, the Coroner (from *Crowner*, or Crown representative who, ever since the 12th Century in England, was appointed to make sure that taxes were paid upon death) is compelled by law to open an inquest whenever an accidental death occurs. This practice contributed to the building of national accounts of accidental deaths. In France, the criminal arm of the Justice department has been compiling statistics since 1826 but has been separating deaths by cause only since 1906 (Chenais, 1974).

Generally speaking, other branches of Government became involved in tallying road accidents and their causes only after World War II. There was a gradual shift from seeing accidents as simple chance events to attempting to explain them. This shift took some 50 years from the Russian of Polish origin Bortkiewicz (1898) to the British Smeed (1949). This slow process involved data gathering and only really took hold with the advent of computers and multivariate analyses. It deserves our attention. The introduction of individual factors in accidents, particularly medical ones, came later. More often than not, it focused on the construction of cross tables, on simple "before/after" tests, or used control groups to modify one variable at a time, "cause" and "effect" being linearly associated. Cross tables are rarely multivariate because their very design severely limits the number of factors that can be jointly taken into account.

1.9. Road accidents, criminal acts, acts of terror and acts of war

Let us turn to the definitions of deaths deemed "accidental" in the literature, *i.e.* of all deaths classified in Column A of Table 1. In principle, columns D and E refer to different kinds of literature dealing with crime or war. But some common elements can be found: first, all are generally defined as the result of a combination of systematic and random factors; in addition, the frequency of road accidents and that of terrorist acts or of acts of war are often explained by some common factors.

To better illustrate this commonality, let us quote the great historian A.J.P. Taylor who associated road accidents directly to wars in the sense that "There are some conditions and situations that make them more likely, but there can be no system for predicting where and when each one will occur". We will come back to this combination of systematic and random elements, for individuals and groups, later.

A particular common factor is the disproportionate number of young men in a population (Bouthoul, 1970; Heinsohn, 2003), found today to be a recurrent factor in the frequency of wars and acts of terrorism. Figure 7. A shows that the same variable, an "age-sex" quality index of drivers, can be studied over time and by country. In fact, few multivariate analyses of the frequency of accidents on roads do without this age-sex indicator. The aging or rejuvenation of the population of licensed drivers will have a predictable impact on the average ratio of the risk per kilometer. Heinsohn's famous "youth bulge" view (2008) belongs

to both literatures. On the other hand, some variables that look alike, population density for instance, provide very different explanations for wars (in Black Africa especially), where it is linked with land appropriation, and for road accidents, where it is linked with traffic congestion and road user categories.

Weber (1970, 1971) opened the door to eventually associating road accident and criminal behavior. A number of authors today, like Brace *et al* (2009), are exploring this association, seeking to make sense of the positive correlation between criminal behavior and risk taking at the wheel of a car.

2. The idea of random events and the data to be explained

To understand the evolution of thought from the initial collection of data on road accidents to the actual models which seek to explain them, let us consider two of the best known statistical representations of chance events: the Gaussian bell-shaped normal distribution (Gauss, 1823), known to all students, and the Poisson distribution (Poisson, 1837), adapted to "small" numbers as first described in: *The Law of Small Numbers* by Ladislaus Bortkiewicz, published in 1898, known to all researchers. The idea of plotting and analyzing accidents systematically is attributed to Bortkiewicz who, like Student, rediscovered Poisson's law and applied it to tables which described the number of soldiers of the Prussian army who were killed by blows from their horses. Bortkiewicz thought that these events were perfectly random, but we will point out that the question is in fact more complex because the mean of a variable that may seem random may shift, both for rare ("small number") and frequent ("large number") events.

2.1. The horse and the birth of individual modeling

2.1.1. Horses and accidents: towards a first discrete model of individual outcomes

Bortkiewicz's built a table giving the number of soldiers in the Prussian army killed from their horses' kicks each year, in 10 of 14 cavalry corps, over a 20-year period (1875 to 1894). This army was the largest in Europe after the French-Prussian war of 1870. The total number of soldiers killed gave an average of r = 0,61 [=122/200] deaths per corps per year, a rate inferior to one. Bortkiewicz showed that the numbers in his table followed a Poisson distribution, and he illustrated clearly their frequency, Figure 1 showing the following values: 109 corps-years without deaths, 65 with 1, 22 with 2, 3 with 3 and 1 with 4 victims.

Figure 1. Poisson distribution, by army corps, of the number of Prussian cavalrymen killed by their horses' kicks, from 1875 to 1894
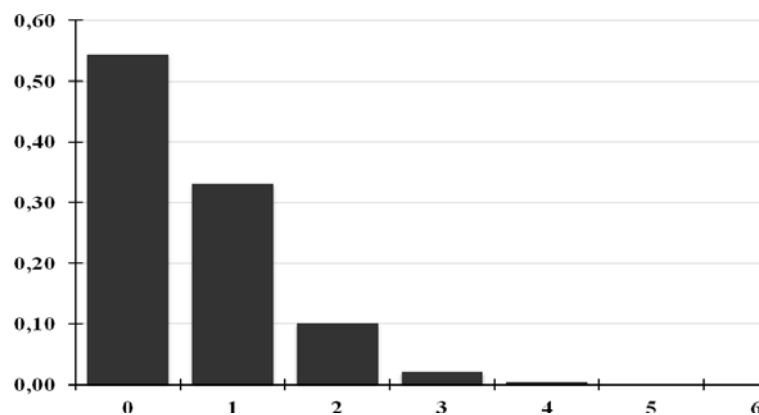
For a long time after Bortkiewicz, his distribution was considered to be an illustration of pure random events. But it was also discovered that the army kept a logbook containing more than 15 entries of information (including religion) for each soldier. These data later showed that the values obtained by Bortkiewicz varied according to the year and to the army corps of the soldier and that those values shifted the averages, if ever so slightly (Preece *et al*, 1988). The categorical data (also called Boolean, meaning that they are represented by 0 or 1), used to identify the year and the army corps, were in effect systematic variables: accordingly, maybe different army corps obtained their horses from different breeders, maybe the horses were of different breeds, or maybe the horses were affected by particular weather conditions one year more than the next. This means *explaining* a variable that is random and follows a certain distribution: it is therefore possible to "model" randomness, *i.e.* to find the factors that influence (at least) the average of chance events while still keeping them random about this mean.

2.1.2. The first explanatory model of individual outcome data in 1970

One had to wait a long time between Bortkiewicz and a model of accidents "with a regression component" proper, as one says to express the fact that the "propensity" parameter of the distribution in fact depends on various factors. The first of these models of the individual frequency of accidents is attributed to Weber (1970, 1971). He designed it, using 5 explanatory variables, to explain 148 000 California accidents reported independently from their severity.

His explanatory variables for the frequency A_t of accidents for the year 1963 were: the density of traffic, the driver's age and driving record (A_{t-1}, the number of accidents for the previous 1961-1962 period), and the driver's police record (with 2 types of convictions for the previous 1961-1962 period). Weber's innovative inclusion of variables such as the driver's past driving and police records laid the groundwork on which later models were founded and designed. His seminal specification will be much imitated later (*e.g.* Boyer *et al*., 1988; , 1994, 2012 *et al*., 1993) but hardly ever cited[6]. The next stage was aggregate modeling, relying on official data.

2.1.3. Road transportation and accidents in the 19th Century

In 1970, birth year of modeling with individual data, modeling based on aggregate official data was already well on its way since 1949, no doubt due to the existence of relatively long official series on accidents in a large number of countries. Even in the 19th Century, much could have been done with official data on accidents involving horses or horse-drawn carriages if the regression techniques had been available.

For France, Figure 2 compares the number of deaths caused by horses and carts since 1854 to deaths caused by automobiles since the first reports which appeared in 1906. The two series meet and cross between 1920 and 1925. Accidents involving horses and horse-drawn carriages peaked during the period 1866 to 1869 (when the French territory was the same as it is today)[7]. Given an average of 1 356 deaths per year for each of these four years for a population of 38 million, the comparable number would be about 2 212 deaths today: the 19th

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[6] Figure 7. B shows how easy it is to compare two samples of individual drivers, the first taken at random and the second taken from those convicted of some Highway Code violation and to show that such convictions are good predictors of the relative risk of having an accident in the following period.
[7] In Figures 2, 5 and 6, the territory of 1854-1859 excludes Nice, Savoie and Haute-Savoie, and that of 1906-1913 excludes Alsace and Lorraine.

Century includes numerous years for which stagecoaches killed more than 1 000 persons[8] in France.

Figure 2. Road deaths caused by horses, horse-drawn carriages and automobiles, France, 1854-1938
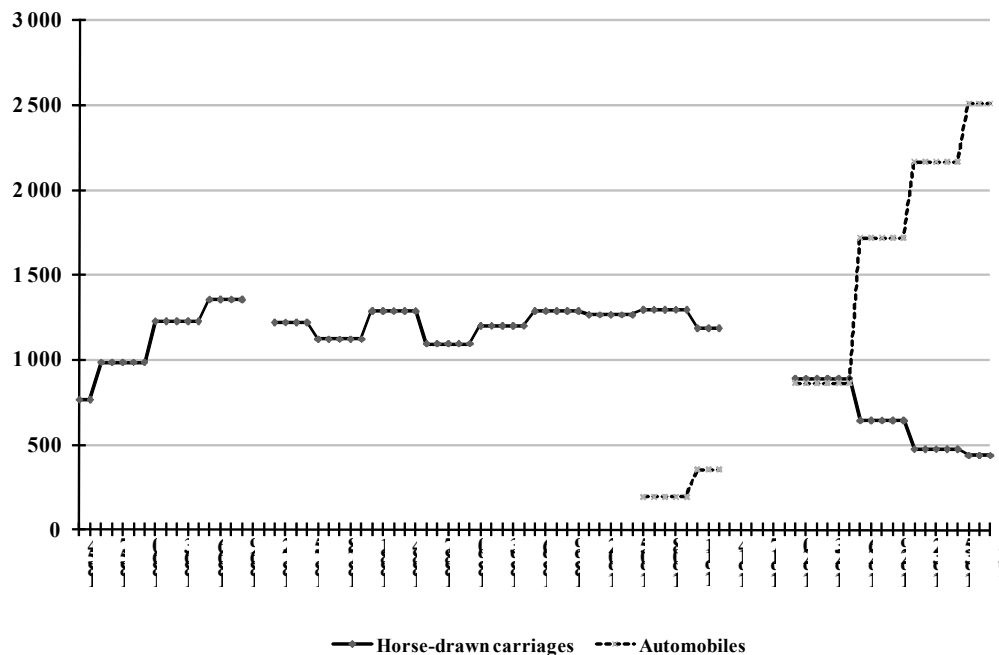
2.2. Horse-drawn carriages, automobiles and the birth of aggregate modeling

Statistics on road accidents and deaths evolved incrementally during the first half of the 20th Century. But it was only in 1949 that Smeed tried to explain sets of large numbers that fit Gaussian distributions better than Poisson distributions, at least in the sense that a Gaussian hypothesis on the distribution of errors in a model[9] of national aggregate statistics seemed reasonable. Let us examine these statistics, notably for reliability.

2.2.1. Road statistics specific to the 20th Century

In 1953, France improved existing road accident statistics with additional data, compiled from police reports of accidents causing bodily harm (called BAAC). This was undertaken by the S.E.T.R.A (*Service d'Études Techniques des Routes et Autoroutes*), a division of the Transportation Department. At the time, a number of industrialized countries did the same, though some Eastern European countries considered that statistics on road accidents, collected by the military, needed to be kept secret.

2.2.2. Errors of observation and sample variance

Conventional statistics do influence the data on the total number of people killed on roads because they only take into account either the number of persons killed on the spot or those deceased within a certain period following the accident. In France, this delay period varied

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[8] Starting in 1901, tramway accidents are included.

[9] His working hypothesis referred to errors in the log-linear regression he specified.

from 1 day (1950-52) to 3 days (1953-66)[10], to 6 days (1967-2004) and 30 to days since 2005, in accordance with the international norm. The numbers pertaining to Metropolitan France used for Figure 3 were standardized in accordance with this 30-day norm.

The impact of such reporting rules on the variance of any series for France-wide fatalities (*e.g.* on monthly values used in some models) is not very well known, but is probably small. The statistics on the number of persons injured are generally less reliable[11] than those on persons killed. Nonetheless, given that they have been compiled systematically as time series, they provide information that can be correlated with explanatory variables and used in modeling as long as the main observational errors become part the regression error or are proportional to the real values.

When comparing data provided by insurance companies with national statistics compiled from police reports, one notices that both carry some error: typically, the number of deaths is relatively accurate and the number of injuries is under-estimated, but not in all countries: in Algeria for example (Himouri, 2008), the national statistics are reliable if the Sidi Bel Abbes Register, showing that the number of injuries reported by police is slightly overestimated, is representative of all 48 wilayas. Similarly, statistics on injuries in Quebec are also sufficiently reliable for modeling despite the fact that the no-fault insurance system, in place since March 1978, induces some moral hazard for injuries declared *ex post* to the Insurance Board (RAAQ) but not reported to the police, and no doubt even for accidents that are so reported on the spot.

In cases of exact proportionality between real values and observed values, the elasticity calculated for the models of these aggregates will not be affected, but the regression coefficients will be in direct proportion to the rate of coverage. Student's *t* statistic (due to Gosset (1908) a hundred years ago) is not modified either if the error is strictly proportional. If, in a model of individual accidents, those are reported at random but the reporting system involves systematic under or over estimation of the average number by alternative, an explanatory logistic regression will have strictly unbiased coefficients, except for the constants (Manski & Lerman, 1977), but this property does not hold for Probit and other discrete choice models. The relationship between observation error on frequencies and statistical model performance is therefore a matter for case by case analysis where the analyst's knowledge makes a difference.

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[10] In 1953, the ratio between the new and the previous measure was 1,2916 (=7166/5548); in 1967, it is 1,0700 (=13585/12696) [another source uses 1,069976 but this has little impact on the variance]. From 1967 to 2004, the number of deaths after 6 days is translated into deaths after 30 days, using the ratio 1,057. The location of the maximum in 1972 is unaffected by these modest proportional adjustments.

[11] The Rhône Department Register in France (pop. 1,6 M) is a good example to use for comparison. The BAAC number of deaths is 99% accurate (Hoyau, 2004)) but underestimates injuries by 38% to 44% (Amoros *et al.,* 2005). Studies using this register (*e.g.* Amoros, 1995) have lead to revised estimates for the whole country (Amoros, 2007). There is no other French Department compiling similar statistics. In Algeria, the comparable Sidi Bel Abbes Register (for wilaya 22) allows the calculation of underestimated and overestimated rates for the country as a whole, as reported by Himouri (2008).

Figure 3. Killed, (30-day delay) on the road by motor vehicles, France, 1950-2011
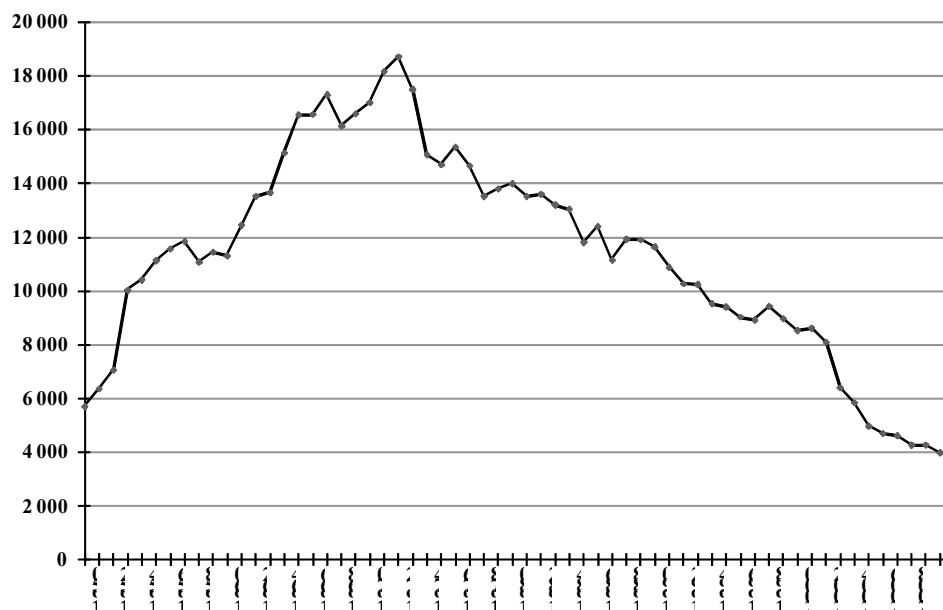
2.2.3. A first aggregate model in 1949

When Smeed studied the total number of persons killed annually on national road systems, he noticed a marked difference among countries, even though all in principle compiled the same information. These differences still persist, even if we take into account the distance driven and look at the annual number of deaths per vehicle-km, as shown in the most recent figures found in Table 2.A.

It could be added that countries like Nigeria and India currently have even higher rates than the highest ones for the countries listed in Table 2.A[12] (from ITF/OCDE/JTRC, 2008, Table A.3). To get a feel for the extraordinary nature of the difference among rates and for their marked evolutions over time, note that the Algerian rate shown in Table 2.B (from Himouri & Gaudry, 2008), which has been divided by 3 since 1970, now stands at approximately 85 but needs to be further divided by about 10 if it is to reach the same level as that for Sweden.

To better understand this phenomenon, Smeed designed a very simple model in which he related the number of deaths per vehicle to the number of vehicles per person, expressed as equation S-1 to S-3 in Table 3 (extracted from Gaudry & Gelgoot, 2002). The coefficients stated for this equation are drawn from S-4, based on a first sample of 20 countries for the year 1938. In S-5, Smeed included 17 of the previous 20 countries studied, but his sample itself pertained to a longer period of time. Equation S-6 pooled yearly values for 26 countries over a number of years.

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[12] Vietnam, population 85M, had 12 000 deaths on roads in 2006 and 10 397 in 2008. Since 2005, fatalities are falling in China and Russia but still increasing in Brazil and India.

Table 2. Number of casualties per billion car-km and by network, 22 countries, 1970-2005

A. 21 countries	Killed per billion vehicle-km				
	1970	**1980**	**1990**	**2000**	**2005**
Australia	49.3			9.3	7.9
Austria	109	56.2	27.9	13.2	9.3
Belgium	105	50.0	28.1	16.3	11.5
Canada				9.5	9.2
Check Republic		53.9	48.3	37	25.6
Denmark	51	25.0	17.3	10.7	7.7
Finland		20.6	16.3	8.5	7.3
France	90	43.6	25.7	15.1	9.6
Germany		37.3	20.0	11.3	7.8
Great Britain	37	21.9	12.7	7.3	6.4
Iceland		21.1	13.5	16.0	
Ireland		28.4	19.2		
Japan	96	29.3	23.2	13.4	10.3
Korea				49.5	18.3
Netherlands		26.7	14.2	8.5	
New Zealand				12.4	10.3
Norway		19.3	12.0	10.5	6.1
Slovenia	167	96.1	65.1	26.7	16.6
Sweden	35	16.4	12.0	8.5	5.9
Switzerland	56.5	30.9	18.5	10.4	6.6
United States of	29.7	20.9	12.9	9.5	9.0

B. Killed per billion vehicle-km, per month, Algeria, January 1970-December 2002
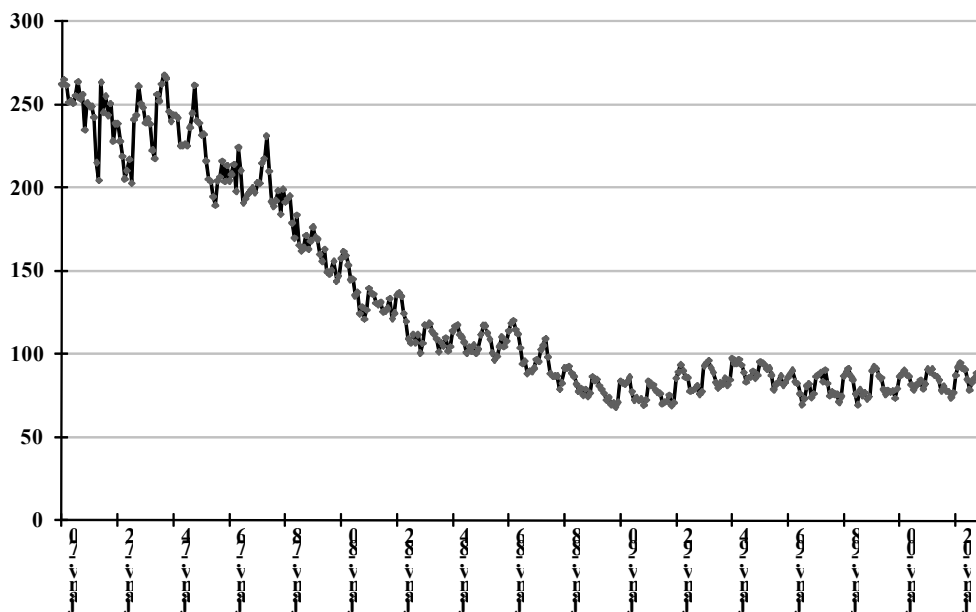
Figure 4 presents Smeed's own data, along with similar data from 26 countries, extracted from the MAYNARD-DRAG data base (Gaudry *et al*., 2002). It is immediately obvious that the relationship found in the 1938 data set tends to gradually level off: Smeed's S-4 model forecasts a greater number of deaths than those recently observed in these highly motorized countries. As the value of R^2 shows, as one passes from S-5 to S-6, his adjustment much worsens over time.

Table 3. Smeed's own regression using his data and applied to a broader sample

	Theoretical and estimated equation		Period	n	R^2
S-1	(Killed/Vehicles) =	k (Vehicles / Population) $^{-2/3}$			
S-2	(Killed) =	k (Vehicles) $^{1/3}$ / (Population) $^{-2/3}$	n.a.		
S-3	(Killed) =	k (Vehicles) $^{1/3}$ (Population) $^{2/3}$			
S-4	Ln (Killed) =	$Ln\ (k)$ + **0,333** Ln (Vehicles) + **0,667** Ln (Population) *(n.c.)* *(n.c.)*	1938	20	
S-5	Ln (Killed) =	$Ln\ (k)$ + **0,408** Ln (Vehicles) + **0,699** Ln (Population) *(16,31)* *(20,41)*	1938-1946 **(*)**	210	0,98
S-6	Ln (Killed) =	$Ln\ (k)$ − **0,058** Ln (Vehicles) + **1,100** Ln (Population) *(-3,36)* *(55,92)*	1965-1998	918	0,88

where: Ln denotes the natural logarithm; the values in parentheses are Student's *t* statistics; n.c. ≡ not computed; the S-5 sample is Smeed's (1949); S-6 is from MAYNARD-DRAG (Gaudry *et al*., 2002).

(*) The 17 countries of S-4 comprised in S-5 are:

Portugal	Finland	South Africa	Canada	Australia	U. S. A.
Ireland	Norway	New Zealand	Italy	Netherlands	Switzerland
Northern Ireland	Sweden	Denmark	United Kingdom	France	

Some of the problems associated with pooling data from different countries can be avoided by limiting the analysis to only one country while still obtaining large changes in relevant variables. In France, for instance, the total number of private cars on the roads, measured on the first of the year, has increased every single year, between 1950 and 2007, from 1 525 million to 30 400 million (a multiplication by 20), as the population increased at a yearly rate of only 4.7% (from 1949 to the middle of 2006).

In this spirit, Page (1997, 2001) reexamined the multinational data using a broader sample of countries and seven variables instead of two. And, like Smeed, he used a logarithmic mathematical form for all variables, but found that the regression errors were not, in fact, stable. To dodge the problem, he ignored the presence of first order autocorrelation of the residuals altogether and made no attempt at obtaining a stationary relationship from first or higher orders of autocorrelation or under different forms of the variables.

It is difficult to pool comparable time series from many countries because of the unavailability of many of the desired factors on a consistently measured basis. This explains why, in spite of the influence of Smeed's fundamental multinational work on the subject, the greatest advances in aggregate modeling will be in fact be achieved with models developed at the national level rather than with pools of national data sets.

Figure 4. The evolution of Smeed's relationship over time
(Killed per 10 000 motor vehicles *vs* number of vehicles per 1 000 inhabitants)

4.A. Smeed's own data, year 1938

4.B. MAYNARD-DRAG data, year 1965

4.C. MAYNARD-DRAG data, year 1970

4.D. MAYNARD-DRAG data, year 1980

4.E. MAYNARD-DRAG data, year 1990

4.F. MAYNARD-DRAG data, year 1998
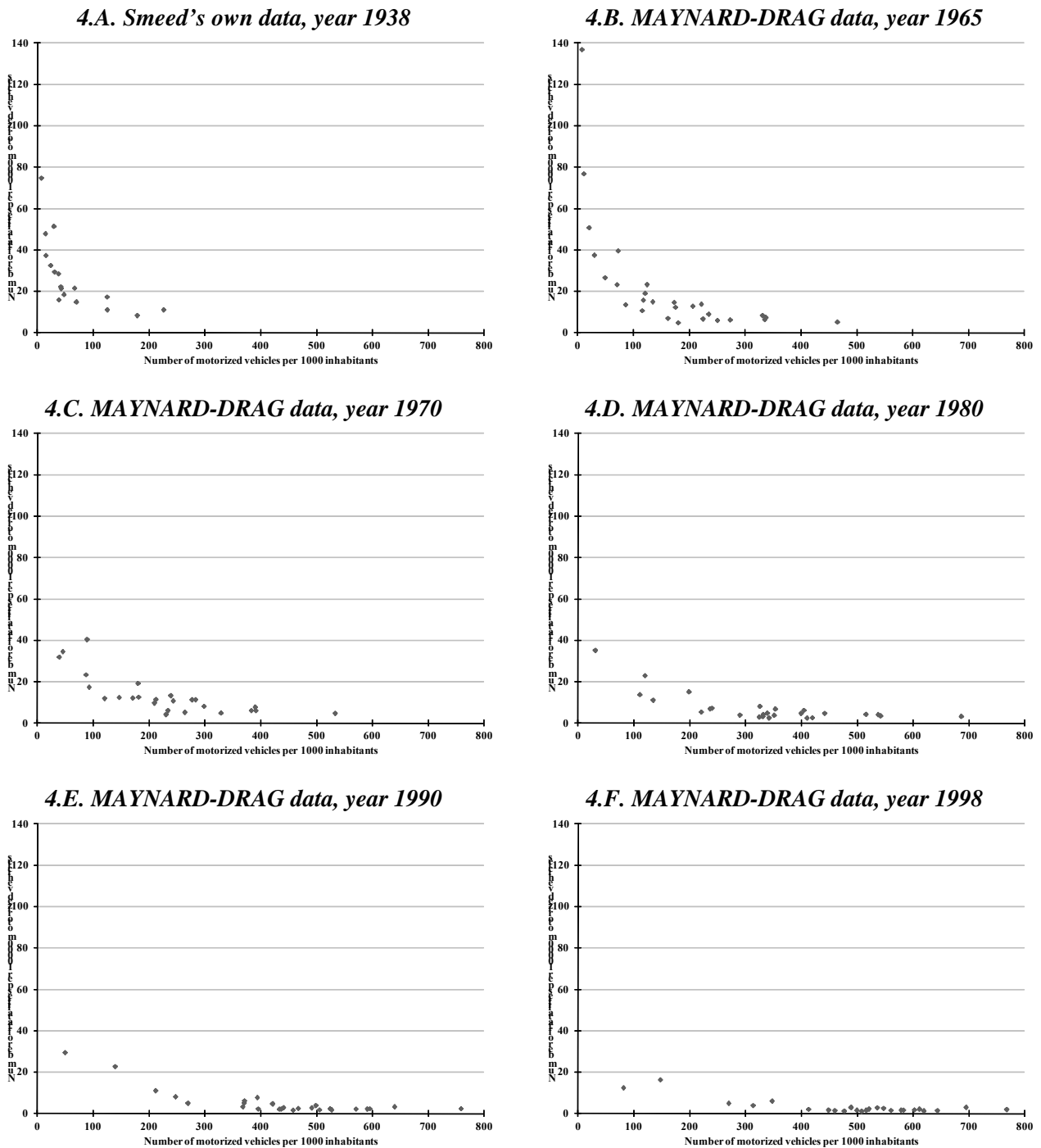
2.3. The two branches of modeling: individual and aggregate

We can summarize the two branches of multi-factorial modeling that originated with Smeed and Weber by two stylized equations. First, the discrete models focus mostly on frequency, independently of concerns about the severity of accidents; the aggregate models focus almost exclusively on the number of deaths. Thus we have:

(0-1)   [Probability of accident]   ← p (various factors; Poisson error)

(0-2)   [Number of deaths]   ← f (various factors; Gaussian error)

The failure to give an adequate representation of the frequency of accidents by severity category will linger right up to the present and is still very pervasive, save for a few occasional improvements where a breakdown by category is found, and this only in certain aggregate studies. Of course, treating the frequency of accidents of all severity levels as a homogeneous measure amounts to a simplistic demand system where substitutions among severity categories is excluded from the beginning or relegated to the study of their conditional severity (the severity measured after accidents have occurred). The first researcher to explain the frequency of three categories of crashes with as many distinct equations was Peltzman (1975) who built an annual multiplicative model with 6 factors explaining the number of deaths, of injuries and of accidents with material damage (all per unit of total distance driven), his barely adequate sample covering only 18 years for the Unites States.

2.4. Trends, long and hard to understand, in 155 years of annual data

The full challenge facing modeling, whether aggregate or not, goes far beyond simply trying to explain variations in levels of victims over such surprisingly short periods of time. The modeling challenge is to explain why certain indicators have sometimes followed the same trend over very long periods of time. One of these indicators is the number of deaths per kilometer driven. The reduction of this number, at least as important as the reduction in the absolute number of road fatalities, is obvious in Table 2, but it is also true when applied to much longer periods.

2.4.1. You can't stop progress

The truth is that, even if we cannot rely fully on the accuracy of the estimates of average annual distance covered per person and transportation mode[13] compiled by Grübler (1990) for metropolitan France from 1800 to 1990 − they indicate a multiplication by 500 of average road distance over 150 years (Part 3, Figure 27) −, it is clear that the present annual toll of somewhat less than 4 000 deaths in France implies an improvement of more than an order of magnitude in the actual road fatality rate per person and kilometer since the war of 1870. Even the peak number of 18 713 deaths (30-day delay) reached in 1972 (Figure 3) was a vast improvement over the era of the stagecoaches.

We find similar improvements for other modes of transportation, such as railroads. The data presented in Figure 5 indicate an important reduction in the number of deaths per traveler-kilometer, using again Grübler's estimates of distance traveled by mode. Interestingly, the comparison between Figure 2 and Figure 5 reveals that in 1925 the number of deaths registered for each mode of transportation, (*i.e.* train, horse, stagecoach and car) was the same, about 900.

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[13] From 100 meters per day on horseback in 1850 to 50 km per day by car or bus in 2000.

2.4.2. Differentiated impacts of accidents on categories of population

Accidents are not distributed evenly over the population. In France for instance, as in many other industrialized countries, two thirds of fatal accidents occur on secondary roads, not on major highways. The drivers found in large cities rarely use back roads where very high rates are observed. But other seemingly hard facts, such as the proportion of women among road victims (see Figure 6), also beg for explanation: this proportion varies over time, as it does by mode of transportation, but it always remains much lower than 25% of all accidental deaths before 1938.

If this proportion ever reached 50%, it would no longer contribute to the increasing difference in life expectancies between men and women, a growing source of inequality between the sexes since the 19th Century. It is interesting to note that the maximum level of accidental deaths involving women coincides with the moment when all three modes of transportation have the same value. This occurs around 1925, but their ranking remains more or less the same over time: cars always take the bigger share of casualties, followed by horses and, much lower on the scale, by trains (save for a very short time period at the turn of the 20th Century).

Figure 5. Casualties caused by automobiles and by trains, France, 1866-1938
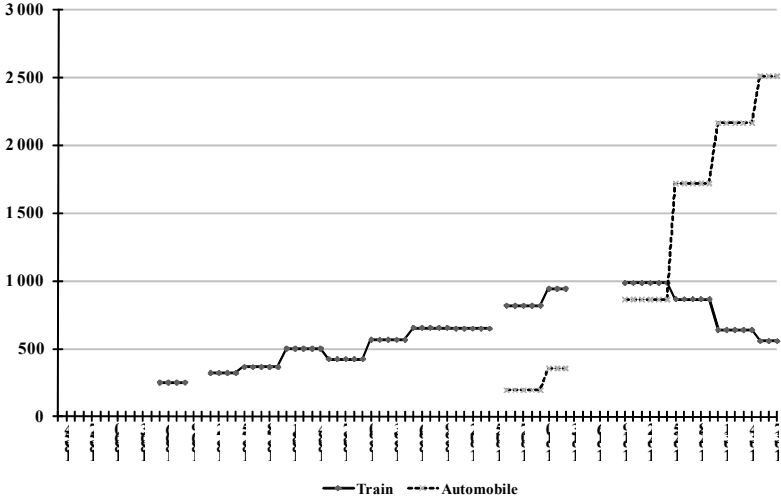
Figure 6. Proportion of women among casualties, by mode, France, 1866-1938
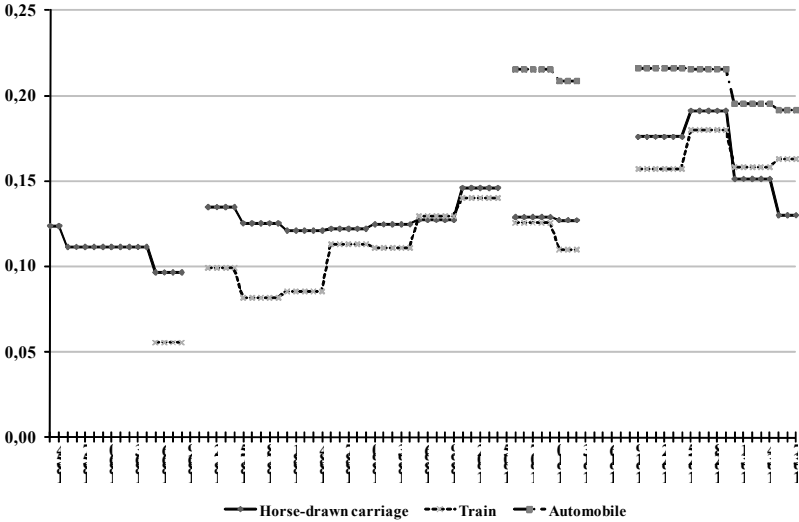
2.4.3. A Turn of the Century assessment: from the dung engine to the gas engine

The transition from horses to horsepower in the 19th Century removed a major source of accidents in the cities. In fact, not only were horses much more dangerous than cars are today, they created all sorts of other problems. Called "dung engines" for obvious reasons, hackneys polluted much more than cars[14]. Heaps of dung littering the streets of cities (from 6 to 12 kilos per horse every day, corresponding to an average annual consumption of 1.2 tons of cereal and 2.2 tons of hay[15]) — became the locus of flies, which spread disease like typhoid fever and infantile diarrhea. They were also a major source of methane gas. In addition, each horse sprayed about a liter of urine every day on the streets. Horses were also noisy (their shoes hitting the cobblestones) and their cadavers were difficult to dispose of – they had to be picked up and brought to a dump[16]. The gas engine and the cars have thus saved us from the pollution generated by horses, whose untenable ecological footprint, moreover, hindered the growth of the economy.

3. A public health approach: knowing how but not why

How can one make sense of such secular trends? The seminal Bortkiewicz-Weber and Smeed single-outcome formulations gave rise to a pair of parallel streams of explanations of road accidents, distinct to this day, that share a "public health" epidemiological emphasis on the establishment of multiple correlations giving rise to testable corrective policy intervention hypotheses.

Both of these modeling traditions effectively aim at understanding something of the evolution of nation-wide totals and accept in practice (i) that successful intervention does not require understanding why improvements have resulted from policy actions taken (ii) and that changes occurring in the absence of any action might never be made sense of. Let us consider examples of both stands.

3.1. Acting effectively without understanding why it works

3.1.1. Vaccination saves lives

There exists practical *knowledge of how* without theoretical *knowledge of why*. Consequently, it is possible to intervene without understanding why the chosen action produces the desired effect. A good example of this is the smallpox vaccination whose efficacy was systematically established by Edward Jenner, starting[17] in 1796. The practice of vaccination was so obviously effective that Jenner convinced the British Parliament to make smallpox

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[14] Morris (2007) compares casualty rates involving hackneys in cities a hundred years ago to the present's rates involving cars. For New York, the rate in 1900 was 75% higher per citizen than in 2003; in Chicago, the casualty rate per vehicle was 16,9 times higher in 1916 than in 1997.

[15] For instance, an Orion, which is a French carthorse, consumes 2,5 tons of cereal, straw, fodder and granules per year. On average, a horse produces 8-20 kg of manure and 3-4 liters of urine per day.

[16] Morris (2007) estimated that in 1880 New York, the city had to get rid of 41 dead horses every day (15 000 per year). Theses numbers are explained by the intensive use of the animals arising from their high ownership costs, roughly equal per year to their capital cost: in 1820, the life expectancy of horses pulling tramways was less than 2 years. Railway companies were the major owners of horses required for the terminal (access and egress) movements of goods at rail stations.

[17] We discount various inoculation practices attested by numerous individuals in Europe, or in some tribes (for instance Turkish), where the systematic approach to trials seems absent and devoid of observable influence on medical practice and local health treatises or laws.

vaccination compulsory. This happened in 1840, 44 years after Jenner's initial work in which he had inoculated a boy with cowpox pus and thereby tested his simple hypothesis that a cowpox vaccine protected from the human variety of the pox disease, as he had noted on his own farm employees. Understanding of the mechanism behind the effects of vaccination came much later: Jenner's practice on humans, which would no doubt be forbidden to-day[18], was established intuitively over 44 years of empirical trials.

3.1.2. Speed kills

Similarly, some changes in road safety performance are illustrations of the same kind of linkage between observed variations in counts and their underlying determination. The clearest example may well be the relation between speed and fatalities. The posting and enforcement of speed limits on roads lowers the number of crash deaths, but there exists no standard account of the causal chain between the speed limit and the result. We do not understand the effect of factors such as a driver's concentration, reflexes and other psychological variables that obviously play a role in determining the influence of speed limits on the frequency and severity of accidents.

The case of the smallpox vaccine exemplifies David Hume's opinion that our notion of causality stems from a "constant conjunction" between terms. More generally, established statistical correlations point to underlying mechanisms that might be brought into play despite the fact that they are fundamentally not understood and to a large extent random. In that manner, thousands of studies of all kinds have established that interventions limiting speed on roads have saved lives.

3.1.3. Average "intrinsic dangerousness" by age and sex

Similarly, the U-shaped relationship between age and accident risk per kilometer driven shown in Figure 7.A is a structural biological "average" the underlying reasons for which are barely understood. It is known however that some factors, such as certain medical conditions (which limit the issuing of driving permits) and driving experience, influence its shape somewhat. But strictly isolating the exact influence of age and sex from that of all other such factors would notably require understanding how driving experience shifts the curve (in either direction) according to the age and sex of the driver. Bolduc *et al.* (1993, 1994, 2012) have certainly identified factors that, by helping to distinguish between age and experience, help to pin down the strong biological U structure.

Such U-shaped curves often describe the risk only as a function of age: see Malek & Hummer (1986, Figure 2) or Williams & Carsten (1989) for the United States and Johansson (1997, Figure 2) for Sweden. If and when distinct curves are drawn by sex, both tend to have the same risk of accident per kilometer driven in the middle years, as in Figure 7.A. Also, the left hand side of the women's U curve is typically lower and more open than the men's, but the two U cross around their respective minimum, e.*g*., for the United States (Evans, 1987, Figure 4), France (Fontaine, 1988, Figure 6), Germany (Hautzinger & Tassaux, 1989, Figure 7.3) and the United Kingdom (TRRL, 1987, Figure 1).

Figure 7.A summarizes in stylized manner not only those many international cases just mentioned but also a robust Canadian case (Grignon, 1988) where three U-shaped curves

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[18] Similarly, Louis Pasteur's famous experiment on a young boy (a sample of one!) would have been outlawed, if only because he was not a doctor but a chemist.

were established by type of accident (fatal, injury and with material damage only)[19]. Figure 7.A is therefore quite general a stylized representation of what is "expected" of a 20 year-old male driver or of an 80 year-old female driver.

Figure 7. Relative risk of accident and intrinsic dangerousness, by age and sex

7.A. Stylized curves of the relative frequency of accidents per km at the wheel

—Women ----Men

7.B. Relative accident frequency and the number of previous infractions

B.1. Men with 1, 2-3 and 4+ infractions

—●—Men, 1 former infraction ----●----Men, 2 or 3 former infractions —●—Men, 4 or more former infractions

B.2. Women with 1, 2-3 and 4+ infractions

—●—Women, 1 former infraction ----●----Women, 2 or 3 former infractions —●—Women, 4 or more former infractions

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[19] Each curve's numerator includes accidents reported — with a police or insurance company report — for the whole population of Greater Montreal and the denominator includes trips per car where individual mileage is finely calculated by assignment of drivers to the road network. The latter data are taken from a regional Origin-Destination study (CTCUM, 1983). It contains the relevant socio-economic characteristics, such as age and sex, the driver's trips per hour, origin, destination and purpose. These data make it possible to assign all trips on realistic itineraries for a large metropolitan area (population over 3 million) and to calculate quite precisely their length.

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3.1.4 Variability of "intrinsic dangerousness" within age-sex group means

The mean curve exhibited in Figure 7.A hides important differences between individuals belonging to any age-sex sub-group. Consequently, insurance premiums based on such group averages may be financially sound but are actually unfair to many individuals: who ever fits the average of his or her age-sex group? On the other hand, charging the same initial premium to all individuals irrespective of their sex or age (and of the averages of age and sex groups), and then adjusting the premium according to each individual's observed driving record, will be expensive: to determine each person's actual risk, the insurance company will have to wait for enough accidents to occur and for driving records to progressively reveal the relevant "intrinsic dangerousness" of each person, *i.e.* the individual's own risk-proneness coefficient.

Weber (1970, 1971) showed that, when calculated on the basis of past offenses, this coefficient was partially predictable; on the same lines, a recent German study based on the link between violations and accident frequency showed that violations of the Highway Code were associated with higher accident probabilities. But this German study showed much more. In fact, on this subject of relative danger within an age-sex group, the summary presentation by Krupp (2005) of the detailed background work by Schade & Heinzman (2004) first outlines a solid methodology based on three samples: first, a control group of 22 000 German drivers chosen at random to help define the distribution of socio-economic characteristics; second, a group of 60 000 drivers taken from a central registry of traffic violators; and a third group, also composed of individuals whose names appear on the registry of traffic violations but who also have, in the ensuing 12 months, been found responsible for accidents.

The results presented in Figure 7.B show (exposure being approximately taken into account by socio-economic groupings) that drivers listed in the traffic violation registry are very over represented among those having accidents in the next period: nothing added to Weber here. More surprisingly, this over-representation is not associated with any sex or age group but is definitely linked only to the number of traffic violations in the previous year. For all subjects (broken down in Figure 7.B), the relative frequency of accidents jumps from 1,00 (no traffic violation) to 2,15 (one traffic violation) and then successively to 3,52 (for 2), to 4,13 (for 3), to 4,42 (for 4) and to 5,87 for more than 4 traffic violations. Relative risk proneness seems independent from age or sex! Long buried under an excessive emphasis on "education", where convincing results have yet to be produced, risk proneness may be ready for a comeback…

The detailed results, shown in Figure 7.B (from Krupp, 2005), amazingly imply that the average U-shaped curves by sex of Figure 7.A can be broken down among sub-groups, each with its own U shifted vertically (in parallel manner). They do not imply any sort of modification of the shape of the age-sex risk curve based on the average number of violations. As a result, they tend to confirm the hypothesis of the intrinsic dangerousness or risk-taking propensity of certain sub-groups of individuals throughout their lives. The "intrinsic danger coefficient" varies from 1 to 6 within age-sex groups, a magnitude comparable to the variation in the average risk (from 1 to 6 or 7) throughout life. Combining these suggests that a classification by age, sex and relative dangerousness conditional on the means of the former variables could usefully distinguish between some 40 classes.

Differences in intrinsic dangerousness play a role in recessions: in the recent dramatic collapse of U.S. road fatalities, which fell by 22% from 2005 to 2009, fatalities implying

drivers who had 2 or more previous accidents fell disproportionately (Sivak & Schoettle, 2010) from 2005 until 2008 (the last year for which detailed data were available), about twice as much as accidents by drivers who had one or no previouos accidents.

3.2. Neither acting nor understanding: the peaking of casualties in 1972-1973

If modeling and effective intervention do not require a proper causal understanding of linkages, it may also be conversely true that ignorance of statistical linkages imposes inaction. A good example of this ignorance accompanied by a healthy and forced inactivity pertains to the turnaround in road death counts that took place in many advanced countries in 1972-1973 (1972 for France, see Figure 3). If one understood the problem, some policy action might now be advisable to bring forward the peak in countries where it has not been reached yet (Nigeria, India, China, *etc*.). Inactivity may be the wisest course of action if we are too ignorant to make a proper diagnostic and even to ask the question correctly. This long standing ignorance of macro linkages and structures has historical roots.

For instance, Oppe (1991) noticed a simultaneous peak in road deaths in 1972-1973 in 6 countries (Japan, USA, Germany and Great Britain[20], Israel and The Netherlands) and, with others, tried to mathematically reproduce the turning point, but only with descriptive statistical methods, as pointed out by Orselli (2004), thereby failing to provide a structural explanation for the maximum: adjusting a time function, exponential[21] or not, logistic and symmetric or not, to data on distance driven or to severity rates (multiplying them), as in Oppe (1989) or Koornstra (1992), amounts to a description and fails to explain the phenomenon because no policy prescription arises from non structural equation curve fittings. The same objection applies in other contexts to the countless national autoregressive models, with or without "intervention" variables: their interest lies precisely only in their estimates of the ruptures caused by interventions (such as the imposition of compulsory seat belts, major modification of the Highway Code, and fines), namely in the structural variables; it does not lie in the self-explanatory lagged values of the dependent variable or in the mere function of time.

Why then did the number of deaths peak in so many countries (much more than 5, clearly) at the same time in 1972 or 1973 (typically in the same month of August), when none of those countries implemented any significant policy intervention? And why[22] did those very countries peak in 1972-1973 when the peak occurred in 1989 in Spain and in 1995 in Greece (see Table 4)? The 13 curves for the simultaneous national peaks strongly resemble the curve for France[23] shown in Figure 3.

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[20] Oppe neglected both the higher post-war value in 1965 (8143) — the value for 1972 is 8135 — and the true maximum of 9168 in 1941. This sloppiness reduces his count to 5 countries. A less partial list is found in Table 4.

[21] Orselli (2004) noted that a decreasing exponential function with a zero asymptote is "incompatible with the stagnating phenomenon of the reported number of casualties of the roads in developed countries".

[22] Since this peak has yet to be understood, it is absurd to write: "Looking at the data from the last 25 years, it is clear that in most OECD countries, road safety policies have been very successful" (OECD, 1997). It remains unclear why cruising on an undiagnosed downward trend constitutes a success.

[23] Some politicians congratulated themselves for having taken measures others had not taken or had taken later. Such diagnostics attributing the benefits of the trend reversal to local measures, without demonstration, can easily be refuted. In France, for instance, the only measure taken before the turning point of 1972 concerned blood alcohol concentration (BAC), a measure introduced in October 1970. All other measures were introduced later: speed limits (from June 1973 to November 1974), safety belts and helmets (from June 1973 to September 1979). As there was no significant measure adopted by any of the 6 countries studied by Oppe for the 1972-1973

To better understand how significant this trend reversal was, let us look in Figure 8 at 4 important variables aggregated over the 12 countries listed with italicized names in bold in Table 4. Included in this group of 12 are Spain and Great Britain despite the fact that their own peaks occur outside of the 1972-1973 period. Spanish fatalities peaked 17 years after those of the remaining 10 countries; identifying a peak for Great Britain is less straightforward because, forgetting the true maximum (of more than 9,000) of 1941, the 1972 count of 8,135 deaths is almost equal to the 8,143 count reported for 1965. Removing Spain and Great Britain from this group of 12 would increase the steepness of the curve of fatalities without changing the location of its robust peak.

Note in passing that the October 1973 OPEC crisis did not have a significant impact on distance driven in these 12 countries, except for a slight change in its rate of increase. On the other hand, whereas the number of casualties dropped significantly after 1972, the number of persons injured fell less fast. In a proper model, both the peak and the change in the mix of fatalities and injuries would be explained. It is fair to say that we are still far from an explanation of this major structural feature of road safety performance and that, as we shall see in Part 3, this glorious ignorance will not help understanding the current situation of a possible reversal of the 30-year downward trend in many countries. How could a minimum be made sense of if an obvious maximum is still not understood, if it is acknowledged at all?

Table 4. Year of the highest number of road fatalities in 30 countries

Year of maximum	N	Country
1965-1966	2	*Great Britain, Sweden*
1969	1	Czech Republic
1970	4	Luxemburg, Japan, *Norway,* Australia
1971	2	*Switzerland, Denmark*
1972	10	Israël, *Austria. Belgium*, *France*, Finland, *West Germany*, Ireland, Italy, *The Netherlands*, United States of America
1973	2	*Canada,* New Zealand
1975; 1978 ; 1979	1 +(1/2)	Portugal, Iceland; East Germany (before reunification); Slovenia
1989	3	*Spain*
1990	1	Hungary
1991	1+(1/2)	Poland, Korea, East Germany (after reunification)
1995	1	Greece

On this point, the manuscript from which Table 4 and Figure 8 are drawn (Gaudry & Gelgoot, 2002) suggests that one of the variables that could explain the simultaneous national peaks of fatalities in 1972-1973 could be the car occupancy rate. The occupancy rate is of course the inverse of the explanatory variable *cars per capita* shown on the x-axes of Figure 4 pertaining to data for Smeed's model[24]. The other plausible causes, such as the average quality of drivers (due to baby boom induced changes in the age-sex mix) or the modal split (also linked to the

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period, France is an exception among 12 the countries counting for Figure 8. Thus, French editorials (*e.g.* Got *et al*, 2007) linking the 1972 peak to the introduction of speed limits and compulsory seat belts are gratuitously wrong: the French BAC policies were implemented in October 1970 and could not reasonably have caused the August 1972 turning point.

[24] In a conversation at The University of Montreal at the beginning of the in 1970s, Smeed told one of the current authors that he could not explain the soundness of his results. We do not wish to impose on his results a car occupancy rate interpretation, but it is clear that this rate is the mathematical inverse of the explanatory variable he picked for his successful simple model.

youth bulge) must be discarded for the same reason for which Adams (1985) discarded technical improvements.

Figure 8. GDP per capita and road indicators, from 1965 to1998: pooling of 12 countries
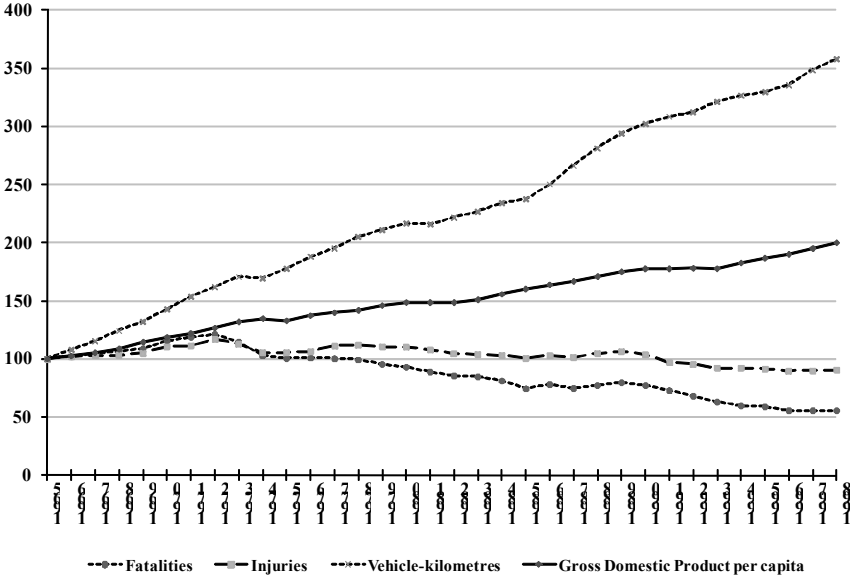
Taking notice of an upward trend break in car sales (starting in 1970) in a number of countries, presumably caused by the arrival on the market of the baby boomers, the same manuscript further suggests that the very important demographic change of the youth wave (bulge) might be working primarily through the vehicle occupancy rate. We shall come back to this issue in Part 3 because it is fundamental to forecasting national and world road safety performances.

We can safely assume that this demographic wave had an enormous influence on the campuses of universities in 1967-1968, on road accidents in 1972-1973 and on job markets starting around 1974-1976. In North America[25], the real average hourly wage has remained more or less constant over the last 35 years, since 1975. In econometric models, major demographic changes cannot be adequately handled simply by the introduction of regulation shifts or of variables that displace the level of dependent variables but cannot explain their turning points. The demographic dimension of many economic models is severely inadequate, and not only in the explanation of road accidents.

Some have started to examine the issue more closely. In reaction to above mentioned manuscript on the "mystery of 1972-1973", Stipdonk (2007) analyzed Dutch statistics over a period of 55 years (1950-2005). He described the evolution of all possible combinations of fatal road accident crashes among pedestrians, two-wheelers, cars, trucks, *etc.* in the hope of making sense of the Cervin-like shape of the 1972 peak for his country. By contrast, Kopits & Cropper (2008) explain part of the decrease in numbers of persons killed since 1963 in 32 countries by the lower number of pedestrians killed, a relevant fact for France (see Figure 14

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[25] The 1974 break in France's unemployment rate is often attributed to Brussels' free market policies implemented in 1974 (Allais, 1999). But this break happened also in Canada and in the United States, two countries that had a baby boom maximum at roughly the same time as France did (two or 3 years after the end of WW II). The demographic wave seems the most relevant variable to explain the trend breaks in both employment and people killed on the roads.

in Part 2), but they fail to address the 1972-1973 turnaround, or even to see it as a turning point.

The dearth of analysis on the single most important feature of road safety since 1950, namely the "mystery of 1972-1973" concerning the turning point in fatalities, leads us to look briefly at the number of injuries (persons injured) despite their noted lack of homogeneity across countries (even for the IRTAD countries[26] applying the same 30-day delay for the reporting of fatalities). Figure 9, for one, seems to indicate that the ratio of injured to killed has been declining in France since 1978 (or 1979 depending on the source), irrespective of the severity of the injury. In a system of close substitutes documented further in Part 2, one would not expect a clear maximum in one component (fatalities) to be without implications for the other (injuries).

Generally speaking, it is simpler to explain a sudden shift (upwards or downwards) in accident trends or in categories of victims of accidents associated with say the implementation of a new law than to explain the trend itself. It is also more difficult to explain a turnaround such as the one that took place in 1972-1973 in so many countries simultaneously than to explain variations about a trend. In many countries, the number of casualties currently shows signs of leveling off, if not of increasing again[27]. This raises an important question: is the downward trend coming to and end, and if so, why? Is a minimum approaching in many of the same countries?

Figure 9. Injured per killed, France, 1965-1998 or 1967-1993
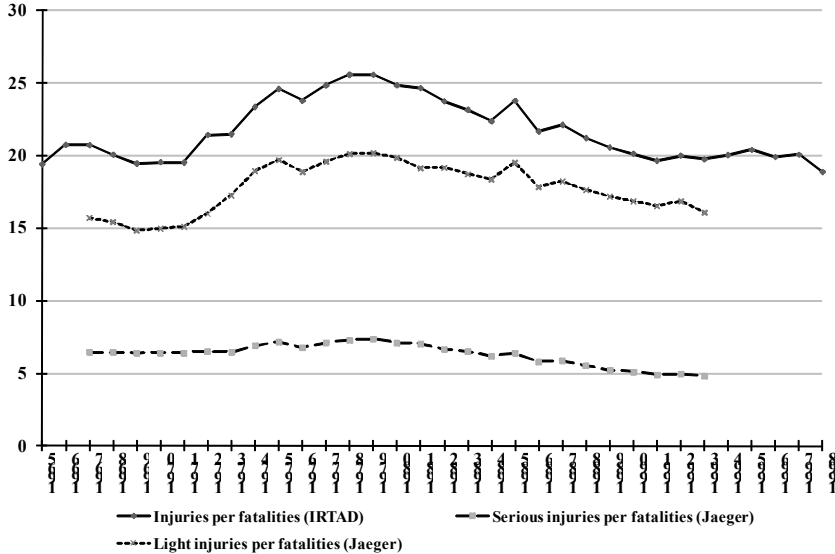
As we see, the discussion on applying a public health approach to road accident policy requires acting upon correlations, simple and multiple, between safety performance indicators and presumed causes: it leads into and requires formal modeling beyond that provided by the founders' single-outcome formulations. But what is involved in doing better that the

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[26] In French: BICAR (*Base de données Internationale sur la Circulation et les Accidents de la Route*). In Figure 9, the 1965-1998 data are from IRTAD and the 1967-1993 data from Jaeger (1997).

[27] In the USA, fatalities, which fell steadily for 20 years after the peak of 1972, started climbing again in 1993 but suddenly fell rapidly by 27% between 2005 and 2010. For the years where detailed data are available (2005 until 2008), disproportionate drops (Sivak & Schoettle, 2010) in peak AM and PM fatalities, in accidents with 2 or more fatalities, in accidents of the less than 25 years of age and in accidents for those with 2 or more previous accidents over the period suggest an extremely severe recession creating unemployment in lower economic groups, notably among the young. A sudden return to the trend would imply an increase of 11 000 fatalities per year.

Bortkiewicz-Weber and Smeed approaches? The difficulties raised by models need some introduction.

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Part 2. Beyond single-outcome models: decompositions of aggregate and disaggregate road safety risk

4. Seven difficulties that modelers have to face

Before presenting a summary of models by type (aggregate, disaggregate) in sections 5 and 6, it is useful to discuss the problems generally raised by models, independently from the type of data used and notwithstanding the comparative advantages of each type. The problems pertain to key dimensions and dictate the nature of the explanations derivable from any model.

In his review of the literature on this topic, Page (1997, 2001) states that the formulation of the DRAG-1 model (Gaudry, 1984 in French and 2002 in English) played a pivotal role in the evolution of road safety performance models. Many other studies on the methodology of road safety analysis, such as the OECD (1997), COST 329 (1999), Reurings & Commandeur (2007) and Antoniu *et al.* (2007), opine with Page.

Page's statements sought primarily to emphasize the new perspective embodied in the DRAG approach, independently from the aggregate or discrete nature of the data at hand ─ actually aggregate in his extension of Smeed's (1949) multinational work, as discussed in Part 1 of this survey. It is therefore useful to isolate the four innovative dimensions that particularly interested him and the other commentators from any other key dimensions of models, three of which will be addressed here.

4.1. Four new issues: decomposition and endogeneity, correlation and substitutability

To simplify a little, road safety performance models (notably aggregate) were formulated before 1984 as simple relations linking, as in Equation (0-2) of Part 1, the number of victims (killed and occasionally injured) to various factors inserted in linear or logarithmic form in the regression, in accordance with the following basic scheme:

(1) Victims $\leftarrow$ (Road Demand, Other factors) [*Performance risk*]

To summarize, DRAG-1 substituted to this direct explanation of the single-level number of road victims (usually casualties) by fixed form regression a multi-level system formulation (with sub-categories) that included simultaneous relationships among endogenous variables of the system, all explained by regression equations with mathematical forms of the variables decided by data rather than *a priori* by the analyst. Consider these changes in turn.

4.1.1. Decomposing outcomes among risk dimensions

The first innovation was to decompose any loss *L* in (1) into a product of exposure *E*, frequency *F* and gravity *G* dimensions, as expressed by the following tautology:

(2) Loss **L = E•F•G** [*Loss Performance*]

which, applied to road victims *VI*, and more generally to material damages if the data are available, may be rewritten:

(3) Victims **VI = DR•A•G**. [*Damage Performance*]

If one then explains the individual components *DR, A* and *G* of this identity by exogenous and endogenous variables, respectively *X* and *Y*, with relevant sub-sets X^d, X^a, X^g and X^y, one can formulate the following relationships:

(4)   Road demand (veh.-km) $DR \leftarrow (\quad, Y, X^{dr})$ [*Exposure risk*]

(5)   Accidents (per veh.-km) $A \leftarrow (DR, Y, X^a)$ [*Frequency risk*]

(6)   Gravity (victims/accident) $G \leftarrow (DR, Y, X^g)$ [*Severity risk*]

where *Y*, the vector of endogenous factors, also constitutes a specific level of the model and, for the formulation at hand, might for instance explain the choice of speed, safety belt, insurance system or blood alcohol concentration. In principle, these endogenous factors can also be explained as part of the model formulation, say with their own layer:

(7)   Driving behavior $Y \leftarrow (\quad, X^y)$.   [*Behavioral risk*]

This first structural innovation allows for the impact of any variable X_k on exposure, frequency or gravity (severity) to be measured separately with equations (4) to (6), instead of limiting the study to that of its net impact on victims in accordance with equation (1). But this gain in understanding requires the formulation of equations for each level, a breakdown long known to insurance companies distinguishing among these three risks by name. Correspondingly, certain consumer self-protection expenses aim specifically at reducing the frequency of accidents while other expenses, called self-insurance measures, aim at reductions the severity of accidents, should those happen: there exists a literature on their estimation, often trying to find indirect measurements of the value of human life and limb revealed by self-protection and self-insurance purchases.

The implicit bet of such a breakdown of outcome risk among specific equations is that each type of risk component behaves in a distinct manner. Such differences may pertain to the size and direction of effects; they may also involve variations in the forms of relationships between explanatory factors and their effects, as discussed below in section 4.1.3.

4.1.2. Endogeneity structure and specific cases of simultaneity

Let us examine the short term behavior of a household and organize the relationships of interest among the likely endogenous variables, *i.e.* those explained within the system for which hypothetical equations must be formulated for the particular hypothetical case considered. For one, the level of household "motorization" [M_i], *i.e.* the number of cars and their technical and safety features, is assumed exogenous even if it becomes endogenous on a medium-term basis. Which relationships are then worthy of further explicitation?

One might think that, for individual *i*, the key short term variables [DR_i , OCC_i], standing for road demand and for the car occupancy rate, depend upon a complex demand for mobility and supply of driving within the household (or, for freight, within firms) and that households (or firms), when deciding on the level of *exposure*, consider at least the expected risk of accident and of its severity [A_i , G_i]*, as shown on line 1 of Table 5, along with many other factors that naturally include exogenous motorization [M_i] in this case.

Similarly, *driver behavior* **[CC_i]** depends on perceived accident frequency and severity risks **[A_i , G_i]***, as described on line 4 of Table 5, and on other factors that the driver has supposedly taken into account in the decision to move other people or goods more or less far, namely in the determination and setting of **[DR_i , OCC_i]**.

On the road, the demand **[DR_i , OCC_i]** and the driver's behavioral vector **[CC_i]** imply an actual frequency and severity risk **[A_i , G_i]** that, as seen in line 2-3, depends on factors other than the system's assumed endogenous variables. In this hypothetical system, the endogenous variables, both explanatory and explained, form a 3x3 matrix where each one depends on the others, in addition to being dependent upon external factors. The resulting simultaneous system formulation will heavily influence the interpretation of the results of the individual equations, as we presently explicate.

Let us for instance imagine that "other factors" in lines 2-3 and 4 include some characteristics of the road such as its *tracé*, geometry, surface and signage. If driving behavior **[CC_i]**, explained (determined) in line 4 and explanatory in lines 2-3, turns out to be statistically significant in lines 2-3, it should be remembered that the road characteristics are then significant there ***given (in addition to) their contribution to risk adjustment* [CC_i] *where they already play a role (in line 4)***: the presence of residual statistical significance in lines 2-3 implies that the objective risk of accident determined in lines 2-3 is not entirely explained by its assessment (how it has been taken into account) reflected in behavioral decision **[CC_i]**, as drivers might involuntarily over or under compensate with respect to their desired (target) risk.

Table 5. Simultaneous structure of a short-term four-level individual model

	Dependent		**Endogenous explanatory**	**Exogenous explanatory**	*Risk component*
1	**[DR_i , OCC_i]**	←	$f^{d,o}$ { **[CC_i]** ; **[A_i , G_i]***;	[Other factors]_i $^{d, o}$ }	*exposure: kilometers and occupation rate*
2-3	**[A_i , G_i]**	←	$f^{a,g}$ { **[DR_i , OCC_i]** ; **[CC_i]** ;	[Other factors]_i $^{a, g}$ }	*accident frequency and severity*
4	**[CC_i]**	←	f^{cc} { **[DR_i , OCC_i]** ; **[A_i , G_i]***;	[Other factors]_i ^{cc} }	*driving behavior (care)*

Since the relationships are simultaneous, it does not make sense to over-simplify the results of the equations formulated in lines 2-3 by statements such as "the design or the geometry of this particular road have such and such an effect on accident frequency and severity". One should say instead: "after taking into account their role in line 4, road characteristics still have — how surprising! — a residual effect on accidents and on their severity in 2-3".

By assumption here, the statistical results obtained[28] suggest that the objective risk explained in lines 2-3 is in fact different from the anticipated risk, because the number of accidents and their severity still depend upon road conditions *even after* their specific risks have been considered and driving behavior **[CC_i]** adjusted: one finds that drivers do not merely have their anticipated level of accidents but a different one that depends on their (correct or incorrect) interpretation (reading) of the road characteristics. Road design and signage therefore indicate (in 2-3) a number of accidents and a severity greater or smaller than the number and severity anticipated (or "demanded") by drivers when they decided (in 4) on a certain level of risk taking.

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[28] For more details, see Gaudry (2006).

In consequence, many regression models relating accidents to a particular feature of road design show weak or unanticipated results in formulations of type 2-3 estimated without the behavioral adjustment term **[CC_i]**: such relationships are not structural but reduced form equations. A recent representative example is the multi-country study of the effect of rut on accidents (Ihs *et al.*, 2011) where it is found that "There are no results showing that deeper ruts tend to increase accident risk generally. Nor are there results that show that ruts have the same influence on the risk for different Average Annual Daly Traffic (AADT) classes at a given speed, or vice versa." Our point is that, in a context of simultaneity, the effect of ruts should be appreciated as residual effects — that can go either way and be significant or not depending on the drivers' reading of rutted surfaces — in the presence of a **[CC_i]** term. In this case, drivers apparently take proper account of ruts in all countries studied, so there is no residual effect to speak of. This does not mean that **[CC_i]** was not adjusted, quite the contrary, and should not have been used in the accident rate equations!

A similar problem can occur if one of the equations of line 4 determines the type of insurance bought or the use of alcohol. Assume that a new law requires lowering blood alcohol levels and that drivers have taken it into account, in **[CC_i]**, when deciding to drive. As the implementation of new laws is normally represented by a Boolean variable included in "other factors" of lines 2-3, its meaning becomes: "after the adjustment in **[CC_i]**, the residual impact of the new law is…". The reason for this is that the impact of the new law measured in lines 2-3 does not correspond to its total impact which first "indirectly" goes through **[CC_i]**: the "direct" effect in 2-3 is — no matter its algebraic sign —, merely a residual effect to be considered over and above that which has passed through **[CC_i]**.

The simultaneous nature of some endogenous variables is normally taken into account *in accordance with the context and the availability of data*. For example, it is extremely rare to have information on driving speeds[29], which, in principle, are a part of **[CC_i]**. In their absence, one or more X_k variables included in "other factors" in 2-3 — for instance the price of fuel— will partly play their role and produce a combined "net" effect. In the United States of America, for instance, the price of gas changes often because States impose their own tax on top of the Federal tax and the former frequently changes with local elections[30]. This situation has led to a number of research studies on the effect of the price of gas on accidents (Grabowski & Morissey, 2004, 2006) by reduced forms (speeds are not observed).

In that sense, every formulation, such as that for DRAG-1 summarized in Table 6, is contextual. The formulation illustrated in that table, which reflects the short term nature of monthly data, is truly simultaneous — but it does not include speed as a variable of the three equations estimated for [CC]: this set only includes alcohol sales, the number of driving licenses issued and the size of the car stock.

The innovation here consisted in defining and structuring the problem as a four-tier system of simultaneous equations, in spite of the fact that the estimated form of the system was recursive and that the equations were estimated one at a time. However, the recursivity shown in Table 6 was in fact a result: tests had shown that, with aggregate monthly data, the risk of accidents has no effect on road demand: [A] and [G] are without influence on [DR]. This result, hardly surprising given the aggregate nature of the data, would have been more surprising had individual data been used instead.

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[29] Certain segments of highways are equipped with speed measuring devices, but they are few and localized.

[30] More so than in France, where the *Taxe intérieure sur les produits pétroliers* (TIPP) allows for regional gas tax supplements since 2007 — but a strict maximum allowable add-on is set for all regions. American States and Canadian Provinces are free to set their own fuel tax on top of the Federal one.

Table 6. Simultaneous structure and recursivity of explained endogenous variables in DRAG-1

Recursive sequence determination for endogenous variables			Endogenous and exogenous explanatory variables
3 ←	← 2	← 1	
Sets of endogenous variables simultaneously determined below: **{ OCC , DR , A , G , CC , V }** ▼ ▼		Demand for mobility and supply of car driving (D$_{CAR}$)	←[.................... , M ,....................]
▼	Vehicle occupation rate **(OCC)**		←[...................., D$_{CAR}$, ...]
VI ≡ ▼ ▼	Demand for road use **(DR)**		←[(——, ————), ———, FACTORS] (X$_1$)
	Accident frequency **(A)**		←[(DR, OCC), CC , FACTORS] (X$_2$)
	Accident severity **(G)**		←[(DR, OCC), CC , FACTORS] (X$_3$)
	Driving behavior (care) **(CC)**		←[......., OCC, ...]
	Realized speed **(V)**		←[DR, ——— , CC , I , ...]
▲ ▲	▲ ▲	Infrastruct. services (I)	←[..]

where the variable that are not defined in the text are:

CC ≡
⌈ V* ≡ *Desired* speed (distinct from *realized* speed V)
| B ≡ Safety belt wearing
⌊ C ≡ Competence ← (Quality (Age/Sex), Vigilance, Ebriety, Insurance régime, Other)

D$_{CAR}$ ≡ Demand for car trips in households, combined with the supply of driving, it determines a road use demand and an occupation rate of vehicles included in vectors DR and OCC, which may contain other similar elements pertaining to freight.

4.1.3. Flexible functional forms and statistical correlations

Another innovation consisted in substituting to predetermined forms in regression, where variables typically appeared in linear or logarithmic form, Box-Cox transformations (BCT) applicable to all strictly positive[31] variables Var_v:

$$(8) \quad Var_v^{(\lambda)} \equiv \begin{cases} \dfrac{(Var_v)^{\lambda} - 1}{\lambda} & , \quad if \neq 0, \\[2em] \ln(Var_v) & , \quad if \to 0. \end{cases}$$

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[31] It is also possible to apply them to variables that contain some null values. For a detailed discussion with transport examples, see Gaudry & Quinet (2010).

The BCT as such was not a novelty in 1984, as implied by the later observation by the renowned economists Davidson & McKinnon (1993) that it was the most common non-linear transformation used in econometrics because it includes the linear ($\lambda = 1$) and logarithmic ($\lambda = 0$) forms of variables. It was, however, bold to use it in a system of nine equations designed to show in particular that the various risk components were each subject to a differentiated and specific explanation.

A price to be paid for such general use of the BCT was to express all results in elasticity form[32] because the β_k coefficients of variables, already difficult to interpret intuitively in a linear regression where units of measurement are easily forgotten, lose all obvious meaning when each variable is raised to a power. In the particular case of logarithmic regressions, the coefficients of a variable found in equations (4), (5) and (6) sum to the coefficient of the same variable found in (1), because the applied breakdown is a product. But, if the risk component relationships (4) to (6) are not logarithmic and all variables are subjected to BCT, the breakdown improves our understanding much further but the coefficients have lost any intuitive meaning and do not add up anymore to those of (1): without elasticities, one is lost.

The use of transformations has even more profound consequences than best fits and due curvatures determined by the data, rather than *a priori*, because they modify correlations among variables and in particular their covariances: hence, BCT affect the existence, size and sign of the β_k coefficients that define and establish the statistical correlations. Another consequence lies in the link between intuition and statistical correlation. Intuition, local and bivariate, is valid if the model is truly $y = \alpha X + \beta$, *i.e.* if it has a quasi-linear, monotonic and symmetric form. But the real model is in fact $y^{(\lambda_y)} = f(X_j^{(\lambda_j)}, X_k^{(\lambda_k)})$, where variables are transformed according to (8), and can even be non-monotonic and asymmetric for several effects. The problem for our intuition is both that the real correlation is multivariate and that the variable-specific transformations are of unknown forms.

One could say that using Box-Cox transformations has epistemological consequences in as much as it deepens David Hume's view concerning the origins of our sense of causality (referred to in Part 1) by showing that it was implicitly made in an intuitive, approximately linear (and monotonic), space when in fact, correlation should be established by an optimal form exercise driven by the data, because form and statistical correlation can only be established together. We may also add that our intuition about accidents is a global one and that it deals with the frequency of accidents but seldom with their severity. Who indeed says: "this variable has a positive effect on the frequency of minor accidents, a negative effect on the frequency of serious ones but no effect on the frequency of average severity accidents"?

The model goes further than intuition. The combination of functional form tests (to obtain sound statistical correlations that are not conditional on *a priori* form) and of results expressed as elasticities (essential if they are to be understood and made sense of) constitutes, for any econometric model, a double-blade Ockham's razor. It will be noted below that aggregate models are here somewhat in the lead over disaggregate models which generally use predetermined mathematical forms and often fail to express all their results as elasticities. "Statistically significant" results can imply silly elasticities, and quite often do.

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[32] Hence, a 10-page section of Dagenais *et al.* (1987) devoted to the theory and measurement of elasticities, including for dummy variables. These developments made it possible to produce tables of results where the elasticities of all variables were systematically calculated in addition to the regression coefficients.

4.1.4. Sub-categories within demand system layers: substitution, complementarity

The fourth innovation is the systematic use of sub-categories within the frequency, severity and road demand layers of the model's central structure framed in Table 6. Whereas the basic distinction between frequency and severity matched the language of insurance, breaking down each by subcategory met the language of epidemiology where morbidity and mortality are classical descriptive categories.

And if *DR*, *A* and *G* are indeed vectors and not scalars, one can detect some substitution or complementarity among all elements, as in complete demand systems. If, as previously mentioned, Peltzman (1975) had been the first to explain a vector of losses, he had not studied his three equations to detect substitution among outcomes, as is common practice in economics; nor had he distinguished between the frequency and severity dimensions of his three totals[33].

In fact, combining insurance and epidemiology categories allows for the search for substitutions (or complementarities) not only within levels of frequency and severity but also among all sub-categories. This is a difficult task, partly because there are many possible outcomes. The resulting system of levels (of say fatal, injury and material loss accidents) by severity category (*e.g.* the mortality of fatal accidents, the morbidity of injury accidents and the loss per material damage only accident) is comparable to consumer behavior systems but far more difficult to model, understand and interpret than consumption good demand systems.

These new substitution/complementarity structures are complex but interesting. It now becomes possible to say: "factor X_{10} increases the total number of accidents, which is good news because total fatalities decrease". Similarly, saying that " cigarette smoking, or using a cellular phone while driving, increases the number of accidents" is of little interest unless we know more about the severity of these accidents: do smokers drive more slowly, and if so, do they happen to have more accidents, but less serious ones? Intuitive judgments on or about "accidents" that do not take severity into account become uninteresting and should be avoided.

There is no doubt that the behavior of drivers is the result of complex and sophisticated daily choices, but that should not be a deterrent to researchers who can no longer limit their analyses of accidents to the number of persons killed. For instance, we can now try to understand the impact of a decrease in the number of deaths on the number of seriously injured victims. The substitution between persons killed and persons seriously injured raises important questions, not the least of which is the life-saving practice of organ donation. Let us examine Figures 10 to 12 on the subject of death ratios (on a constant delay period basis) for France.

In 2005, these ratios changed as a result of the automatic implementation of the 30-day delay period for fatalities, mechanically increasing fatality counts, and because the number of seriously injured drivers also increased following a reporting change in the length of hospital stays (from at least 6 days to at least 24 hours); for minor injuries, the count included stays of 24 hours or less (including cases of no stay in hospital).

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[33] The impact of automobile safety regulations would then probably have been identified more convincingly, had he done so, for one expects self-protection and self-insurance expenditures imposed by governments safety regulations to modify the baskets of demanded outcomes.

This delay period is a significant change in reporting: Figure 10 shows that the ratio of persons killed in France since 2005 will automatically decrease only if the larger numerator is proportionally smaller than the denominator. But a sudden "accounting" increase in the ratio is compatible with the trend illustrated in Figure 10. The matter requires complementary work with hospital admission series. As already clear in Figure 9, the maximum of fatalities in 1972 does not correspond to the maximum of severe injuries per fatality, in 1978-1979; and in Figure 10 the fall in the latter ratio is noticeable.

Figure 10. Seriously injured per killed, victim France, 1967-1993 (Jaeger, 1997)
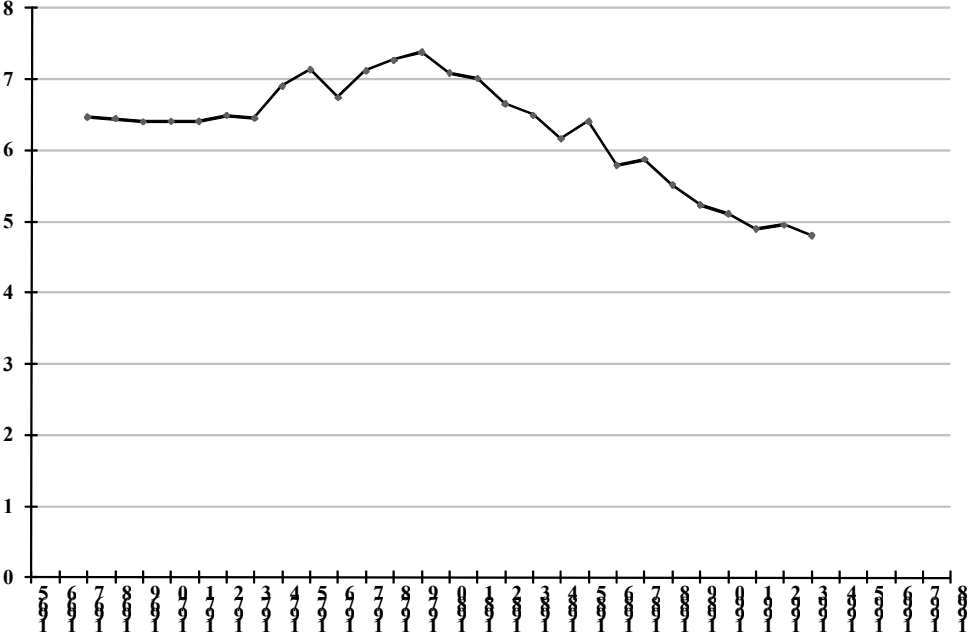
Figure 11. Slightly injured per killed victim, France, 1967-1993 (Jaeger, 1997)
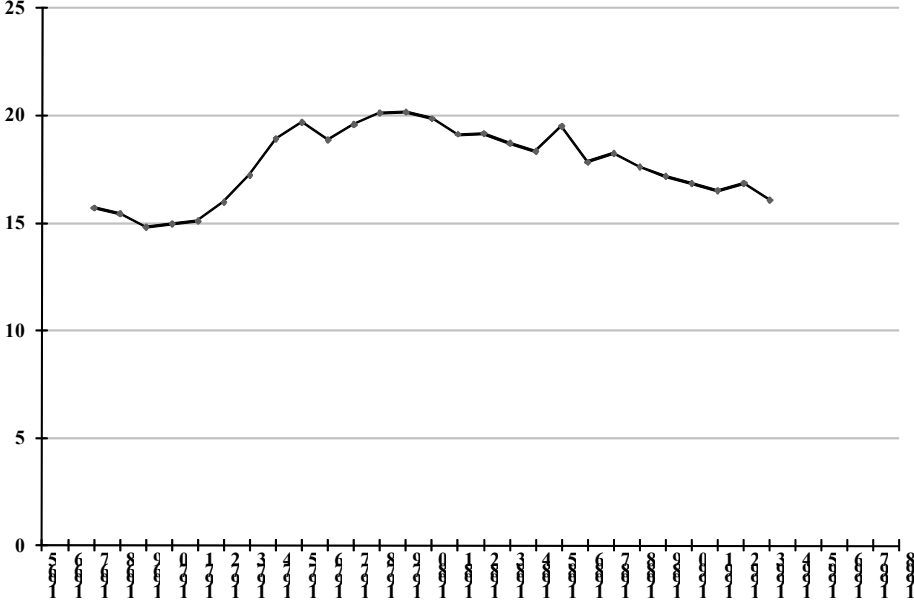
These figures seem to indicate that that the number of seriously injured victims decreases at a faster rate than the number of persons killed. But further analysis can sometimes shows

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otherwise: a Dutch study covering 22 years (Kampen, 2007) discovered that, among seriously injured persons, 8% were uninjured patients kept 24 hours under observation, and 14% were patients with superficial injuries[34]. The researcher's attention was attracted by a ratio that seemed to decrease too slowly. Such an analysis typically shifts the level of a variable but does not necessarily change its maximum or trend. Given that the number of slightly injured victims has been decreasing since 1978 or 1979 (see Figure 11), and given that the number of seriously injured has been decreasing faster than the slightly injured (see ratio in Figure 12), it is possible that the average severity of injury accidents is decreasing. But is the trend in denominator true? To answer sophisticated questions, one needs both good data and sophisticated models.

Figure 12. Seriously injured per slightly injured victim, France, 1967-1993 (Jaeger, 1997)
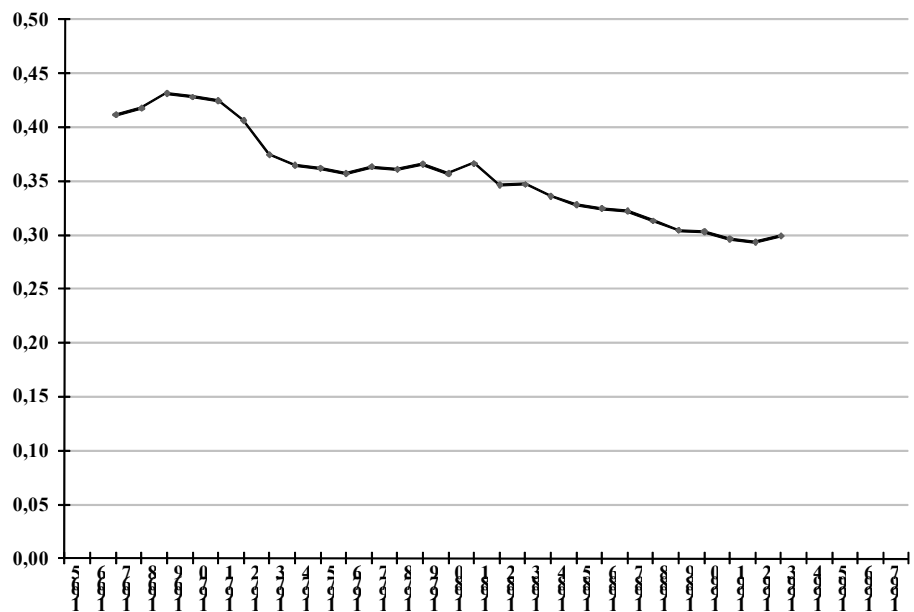
4.2. Other model issues: multivariateness, temporality, data and aggregation

4.2.1. PIMCYÂ multivariateness

Given that every accident by definition implies a driver, a car and a road, it is often said that researchers should concentrate on these 3 pillars of road safety performance modeling. But there is a fourth dimension that models must effectively take account because of its significance: the economic one. The first 3 "constitutive" dimensions of road safety performance, namely cars M, roads or infrastructures I and drivers C, result from a classic microeconomic distinction; but the fourth, activities A, is also fundamental. There are two kinds of economic variables: first, the activities $\hat{A}$ that determine "the sea level[35]" concomitant with each accident involving (by definition of the transport system) some particular values of M, I and C; second, the set of relevant prices P. In addition to these **[P , Â]**, one typically distinguishes between drivers' characteristics linked to competence from socio-economic ones, like income or education level, and one writes **[C , Y]** instead of **[C]**.

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[34] In the Rhône Department of France, studies make it possible to put these numbers in perspective.
[35] Given that the demand for transport is derived from economic activity, the inherent risk is also derived from economic activity. But defining this inherent risk is no easy task.

The variables of interest to road safety performance thus belong to the following 6 categories:

P: Prices (of gasoline, insurance and maintenance, of competitive modes of transportation and fines if they are excluded from **[I]**);

I: Infrastructure (road design and layout, road foundation and surface, road signs, traffic management, law enforcement and weather conditions);

M: Motor vehicles (number, characteristics, condition, weight and nature of load);

C: Characteristics that influence the competence of drivers (age, sex, medical conditions, fatigue and blood alcohol levels, types of car insurance) and more generally, **the drivers' behavior** at the wheel **[CC]**);

Y: Drivers'socio-economic characteristics (income, profession, marital status, cultural and religious factors and the overall characteristics of a population);

Â: Economic Activities (levels, make-up[36] by sector and trip purposes).

In order to construct the appropriate set **[P , I , M , C, Y , Â]** for a given environment, the variables must be chosen and made consistent. Harmonizing variables means modeling them, a practice defined by European scientific committees such as SpotlightsTN for transport (see Gaudry *et al*, 2002), which developed the common SPQR standard for both *data modeling* and *modeling of data*.

Listing all these variables would be too long a task. They vary from the menstrual cycles of women (Liskey, 1972)[37] to macroeconomic cycles, including life cycles[38] that play a decisive role in exposure to risk, amongst many others criteria such as left-handedness (Coren & Halpern, 1991). One could try to list the variables by order of importance, a task never really done well in spite of some worthwhile efforts (*e.g.* Evans, 1990), and which deserves further work. One could also try to clarify and determine the importance of questions such as the left-handed drivers' or the smokers' propensity for accidents (Brison, 1987), or women's periods or pregnancies (Gaudry, 1984, Table 9.9; Fridstrøm, 1997, Tables 6.1.2 and 6.4; Fridstrøm 1999, Table 6.6 and Figure 6.10) and even contraceptive pills (Gaudry, 1984, Conjecture 7 and Table 11).

4.2.2. Temporality

Another tautology, considered interesting by some, is the Haddon Matrix (Haddon, 1968). It has three lines defining the periods before, during and after an accident, in the same way Indo-European languages are grammatically structured with past, present and future tenses. The four columns are assigned successively to the potential victim (or host), to the kind of energy causing damages to the victim, to the physical and the socio-economic environments. But a classification is not an explanation. Naturally, temporality varies with each variable. One does not buy a car every day. This is where the time horizon defines statistical endogeneity, particularly when safety equipment sales are involved as well as the turnover of the car pool.

4.2.3. The nature of the data and aggregation

We have stressed the differences and natural divide between data that can be analyzed by Poisson and by Gaussian methods. But there is an in-between case: that of data made of counts. In the field of applied econometric statistics, space-time aggregation is still in its early stage. Its development has relied mainly on macroeconomic series that are, by definition,

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[36] Trip purposes and the nature of the goods transported have distinctive effects.

[37] In a letter to one of the authors, Liskey said that he excluded from his sample women taking contraceptive pills.

[38] Including working irregular shifts (Liddell, 1982).

aggregates. What this really means is that the cube that combines aggregation levels (discrete, count, aggregate), time factors (cross-section, time series, pooling) and space factors (difficult to define) may be composed of even more empty cells than the Haddon Matrix.

5. Aggregate models: organizing the literature

How are we to organize the literature that followed Smeed's work? First, we must exclude the plethora of simple "before & after" tests[39] and the Box & Jenkins (1970) type of self-explanatory generalizations, with or without the addition of Boolean variables that represent "interventions"[40] (Box & Tsiao, 1975). We indeed insist on the growing multivariate[41] nature of models, because we believe that today's researchers have gone well beyond the cross-table stage, except occasionally for exploratory purposes or for presentation. It must be made clear that we limit ourselves here, and in the following section on individual data models, to estimation procedures that model quantitatively[42], and with multiple factors, the relationships[43] among road infrastructure, traffic, accidents, drivers and the economy.

5.1 Models of one type of damage in one region

A first classification, consistent with Page's (1997, 2001) ideas expressed above, maintains the DRAG-1 border of 1984 but uses it to classify models only by the number of accident categories explained, neglecting the number of explanatory variables or the use of flexible Box-Cox-type forms[44]. This approach yields Table 7 for one-equation models and Table 8 for models explaining several types of damages.

Table 7. Models of one type of damage in a region or country up to 1984

		VI, A, G	DR	P	I	M	C	Y	Â	β_k	n	λ_y , λ_x	ρ_1
1	Crète, 1982	MA*/AUTO		2	2	1		5	1	11	33	$\lambda = 1$	-
2	Maag *et al.*,1982	Killed /Pop.	1			2				3	30	$\lambda = 0$	-
3	Partyka, 1983	Killed			1				4	5	22	$\lambda = 1$	-
4	Stein & Beauregard, 1983	Killed	1	1	1				2	5	26	$\lambda = 1$	-
5	Crandall & Graham, 1984	Killed	1		2	4		2	1	10	35	$\lambda = 0$	-
6	Crandall & Graham, 1984	Killed /mile		1	3	3		2	1	10	35	$\lambda = 1$	-
7	Hoxie *et al.*, 1984	Killed	1			1		2	2	6	72	$\Delta **\lambda = 0$	ρ_1
* Insurance claims per automobile insured for accidents involving material damage only. ** Difference of logarithms.												

All models listed in Table 7, with the exception of the seventh and the last, are estimated with annual data rather than monthly data. The linear form ($\lambda_y = \lambda_{X_1},...,\lambda_{X_K} = 1$) is used instead of the logarithmic form $\lambda_y = \lambda_{X_1},...,\lambda_{X_K} = 0$) in a short majority of models. In addition, the models listed use a relatively high number of variables about motor vehicles **[M]** and economic activity [Â].

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[39] Often found when new regulations, such as speed limits (NHTSA, 1988; Baum *et al*., 1988), are implemented.

[40] Also used to study the impact of changes in legislation on speed, as found in France (Page, 1993).

[41] Building fixed form mathematical models, such as those of Gould *et al.* (2004) for aggregates in the Netherlands, with 2 or 3 equations and a maximum of 3 or 4 variables, is, we believe, pointless.

[42] Which is not the case of computer programs, such as CONCERTO which includes the ACCTOS (Ceausu-Dragos, 2007) and SAARA (Bentebibek & Despres, 2006) modules that do not model quantitatively the relationships of interest.

[43] As a rule, models do not use time as explanatory variable even if tests of its residual contribution as a measure of missing variables are carried out. But the use of simple or multiple autocorrelation turns formally static models into dynamic ones by introducing lagged values of all variables (Spanos, 1987-1988).

[44] BCT give a local approximation of form. Fourier transforms would provide a less local fit.

5.2 Models of multiple types of damages in one region

To better understand Table 8, it is preferable that equations be explicitly written using continuous parameters whose specific values serve to help classify the models as special cases of the general specification. The required three-component regression model, where the BCT applied to variables y, Z_m or X_k, is defined in (8) for each observation t:

$$(9.1) \qquad y_t^{(\lambda_y)} = \sum_k \beta_k \cdot X_{kt}^{(\lambda_{X_k})} + u_t \quad ,$$

$$(9.2) \qquad u_t = \left[\exp\left(\sum_m \delta_m Z_{mt}^{(\lambda_{z_m})} \right) \right]^{1/2} \bullet v_t ,$$

$$(9.3) \qquad v_t = \sum_\ell \rho_\ell v_{t-\ell} + w_t .$$

In this formulation, the regression error u_t can be subjected to corrections for heteroskedasticity and autocorrelation in order to obtain spherically distributed final errors w_t: sphericity parameters appear in the last column of Table 7 and in the last two columns of Tables 8 and 9. For researchers, formulation (9.3) is straightforward, as is nowadays the BCT regression (9.1), a generalization of Ordinary Least Squares, but formulation (9.2) is less known. It describes the way in which the variance of the residual u_t can be expressed as a complex function of some variables Z_{mt} that can also be X_k variables, in which case these determine both the level of y_t in (9.1) and the variance of residual u_t in (9.2) The latter has the advantage of including classic heteroskedasticity as a special case obtained by setting all $\lambda_{Z_m} = 0$ and all $\delta_m = 0$ save one, set at 2. This particular δ_m is found in the last column of Table 8.

The models of the DRAG family are typically estimated using one version or the other of the LEVEL-1 algorithm, notably L-1.4 (Liem *et al.*, 1993). It allows for the simultaneous estimation of all parameters of an equation specified as (9-1)-(9.3), for the formulation of the results as elasticities (for common variables and "dummies") as well as for the restitution of the calculated values of the y_t as expected values of y_t, $E(y_t)$. The latter measure of fit is necessary when a BCT has been applied to a dependent variable, because the measure of adjustment we are interested in refers to the observed variable, not to its transformed values.

Of all the models listed in Table 8, the TAG-1 model for France (Jaeger, 1997) and the DRAG-ALZ-1 model for Algeria, have the advantage of including a measure of average speed on high-level roads of the transportation network[45] that, in the case of France[46], is used to explain the frequency and severity of accidents for country as a whole. The model most tried and tested is the model for Quebec, continuously updated by the SAAQ (*Société de l'assurance automobile du Québec*) from 1999 to 2003. The DRAG-2 version (Fournier & Simard, 1997; Gaudry *et al.*, 1993-1995) already included reversed U-shaped forms[47] applied to total car mileage (a representation of the unobserved underlying traffic congestion). The subsequent version (effectively DRAG-3) includes reversed U-shaped asymmetrical curves, which help predict traffic congestion on a given month (Fournier & Simard, 1999, 2000).

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[45] Sometimes, data are available for regions or states, as in Loeb's (1988) work on the 1979 rural intercity highways of the United States.

[46] For Algeria, the speed series does not cover enough of the network to be used in the explanation of national accident totals or in the explanation of their severity.

[47] Applied to car mileage inserted twice in the regression, once in linear form and once in transformed form according to (8). The Box-Cox value determines if the U is symmetrical as a standard quadratic ($\lambda = 2$) or if the shape of the U form is asymmetrical ($\lambda \neq 2$).

Table 8. Models of multiple damages in a region or country since 1975

Model	Explained occurrences		Region/country considered	Regression					
				Sample		Form		Residuals	
of :	Damages	Severity	[Name of a DRAG family model]	X_k	$t^{(1)}$	$(\lambda_y),(\lambda_x)$	⌒	ρ	δ_m
Peltzman (1975)	Killed 1, Killed 2 Injured Material acc.		United States of America	6	18y	$\lambda_y = \lambda_x = 0$	no	$= 0$	$= 0$
Gaudry (1984) ---------- (1993)	Killed Injured Material acc.	Mortality Morbidity	Province of Quebec [DRAG-1]	44	313m	$\lambda_y \neq \lambda_x$ ---------- $\lambda_y \neq \lambda_x$	no ---------- ⌒	$\neq 0$	$\neq 0$
Gaudry Blum (1993)	Killed Injured 1 Injured 2 Material acc.	Mortality Morbidity1 Morbidity 2	Western Germany [SNUS-1]$^{(2)}$	22	264m	$\lambda_y \neq \lambda_x$	no	$\neq 0$	$= 0$
Fournier Simard (1997)	Killed Injured Material acc.	Mortality Morbidity	Province of Quebec [DRAG-2]	48	445m	$\lambda_y \neq \lambda_x$	⌒	$\neq 0$	$= 0$
Jaeger (1998)	Killed Injured 1 Injured 2	Mortality Morbidity	France [TAG-1]$^{(3)}$	20	456m	$\lambda_y \neq \lambda_x$	no	$\neq 0$	$= 0$
Fournier Simard (2000)	Killed Injured Material acc.	Mortality Morbidity	Province of Quebec [DRAG-3]	48	445m	$\lambda_y \neq \lambda_x$	⌒	$\neq 0$	$= 0$
Tegnér et al. (2000)	Killed Injured 1 Injured 2	Mortality Morbidity 1 Morbidity 2	County of Stockholm [DRAG-Stockholm-2]	33	312m	$\lambda_y \neq \lambda_x$	⌒	$\neq 0$	$= 0$
Tegnér (2004)	Killed Injured 1 Injured 2	Mortality Morbidity 1 Morbidity 2	City of Stockholm [DRAG-Stockholm-3]	35	348m	$\lambda_y \neq \lambda_x$	⌒	$\neq 0$	$= 0$
McCarthy (2000)	Killed Injured Material acc.	Mortality Morbidity	California highways [TRACS-CA]$^{(4)}$	12	96m	$\lambda_y \neq \lambda_x$	⌒	$\neq 0$	$\neq 0$
Aparicio et al. (2009)$^{(5)}$	Killed Injured Material acc.	Mortality Morbidity	Non urban Spanish network [I-DE]$^{(6)}$	21	180m	$\lambda_y \neq \lambda_x$	no	$\neq 0$	$= 0$
Gaudry Himouri (2011)	Killed Injured 1 Injured 2	Mortality Morbidity 1 Morbidity 2	Algeria [DRAG-ALZ-1]	35	456m	$\lambda_y \neq \lambda_x$	no	$\neq 0$	$= 0$
	VI, A	G		Number		Monotonic	U	Sphericity	

1. Monthly ≡ m; yearly ≡ y; *pooling* of cross-sections and time series ≡ p.
2. SNUS ≡ StrassenverkehrsNachfrage, Unfalle und ihre Schwere.
3. TAG ≡ Transports routiers, Accidents et Gravité.
4. TRACS-CA ≡ Traffic Risk And Crash Severity-CAlifornia.
5. There exists an abridged version (2012), presenting only the results of the two equations for accidents with Victims.
6. ID-E ≡ Intercity-DRAG España.

For the majority of months, increased car use result in increased fatalities and increased severity of fatal accidents[48] (increased mortality, *i.e.* increases in the number of persons killed per fatal accident). On the other hand, for some months, more cars on the road have no effect whatsoever on fatalities and on the mortality of fatal accidents. Finally, beyond this maximum, occurring more frequently over the years because car-kilometers increase but few new roads are built, the killed victims and the morbidity of fatal accidents (number of killed by event) decreases. Figure 25 shown in Part 3, will illustrate the fact that traffic congestion saves lives if drivers do not switch to two-wheel motorized vehicles.

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[48] Tests have shown that this did not apply to accidents with injuries or to their morbidity (persons injured by injury accident).

5.3. Multiple-region or multiple-network models, with or without pooling

Sometimes, as in the case of the models listed in Table 9, the sample is created from observations over time on distinct regions of a country or on specific geographical subsets, such as urban *vs* non-urban. The first two models use only one cross section but all others use several, which we name "pooling". We have not found models that explicitly spatialize origin-destination flows and corresponding accidents.

Table 9. Models per region or per national type of network, with or without pooling, since 1949

Model	Explained occurrences		Region/country considered	Regression						
				Sample			Form		Residuals	
of :	Damages	Severity	[Name of a DRAG family model]	X_k	r	$t^{(1)}$	$(\lambda_y),(\lambda_x)$	⌢	ρ	δ_m
Smeed (1949)	Killed		20 countries in 1938	2	20	1y	$\lambda_y = \lambda_x = 0$	no	= 0	= 0
Recht (1965)	Killed/Veh-mi$^{(2)}$ Injured/insured Material/insured		45 American states in 1960	218	45	1y	$\lambda_y = \lambda_x = 1$	no	= 0	= 0
Smeed (1968)	Killed		68 countries 1957-1966	2	68	10y	$\lambda_y = \lambda_x = 0$	no	= 0	= 0
Page (1997)	Killed		21 OCDE countries	7	21	15y	$\lambda_y = \lambda_x = 0$	no	= 0	= 0
Fridstrøm (1999) (2000)	Killed Injured 1 Injured 2	Mortality Morbidity 1 Morbidity 2	The 19 counties of Norway [TRULS-1]$^{(3)}$	48	19	264m	$\lambda_y \neq \lambda_x$	no	$\neq 0$	$\neq 0$
Bergel Girard (2000)	Bodily injury accidents	Killed	France: -tolled highways -high network	8	2	228m	$\lambda_y = 1$ $\lambda_x \neq 1$	no	$\neq 0$	= 0
Gaudry Gelgoot (2002)	Killed Injured	Mortality Morbidity	12 countries and Quebec 1965-1998	15	13	35y	$\lambda_y \neq \lambda_x$	yes	$\neq 0$	= 0
Gaudry Gelgoot (2002)	Killed Injured	Mortality Morbidity	10 Canadian provinces 1965-1998	15	10	35y	$\lambda_y \neq \lambda_x$	yes	$\neq 0$	= 0
Grabowski Morrisey (2004)	Killed/Pop Killed/Mile		All 51 American states except for Alaska, Hawaï and	10	48	216m	$\lambda_y = 0$ $\lambda_x = 1$	no	= 0	= 0
Grabowski Morrisey (2004)	Killed/Pop by age group		*District of Columbia, 1982-2000*	10	48	216m	$\lambda_y = \lambda_x = 1$ (Binomial)	no	= 0	= 0
	VI, A	**G**		**Number**			**Monotonic**	**U**	**Sphericity**	

1. Monthly ≡ m; yearly ≡ y.
2. Total per vehicle-mile and by category: pedestrians, persons involved in one-car crashes and in two-car crashes.
3. TRULS ≡ **TR**afikk, **UL**ykker og deres **S**kadegrad.

This Table includes the 8 variable RES model (Bergel & Girard, 2000), of which there also exists a 5 variable version with traffic and 4 variables related to weather conditions (Bergel & Depire, 2004), *i.e.* without the price and household available income variables. Their Box & Tidwell (1962) formulation, which only uses the BCT defined in (8) on explanatory variables, is close to the formulation of DRAG-type models without actually strictly belonging to the same family. Indeed, it is important to transform also the dependent variable as in (9.1), even if the likelihood function then requires a Jacobean to pass from $y^{(\lambda_y)}$ to y and if this forces the researcher pay special attention to (9.2) in order to obtain residuals of constant variance. A BCT may induce heteroskedasticity, or it may not, depending on the case; if it does, the correction should be carried out simultaneously with the estimation of the BCT using an adequate joint procedure for (9.1)-(9.2).

The issue of differences across regions has been intelligently raised by Orselli (2001, 2003), but none of the models listed in Table 9 seriously deals with it even if the TRULS-1 model designed by Fridstrøm (1999), which is probably the most promising approach for the future of modeling, could eventually provide answers to some important questions such as: (i) what do we gain in shifting from national statistical models to regional models? (ii) how do the regions (19 counties in his case) differ, and could they be regrouped favorably?

By pooling the monthly series of 19 Norwegian counties, Fridstrøm's model is both national and regional. This new approach may eventually be used to explain the differences between modeling national counts and modeling regional ones. And given that his national model contains 19 regional models based on 264 observations, it may also help us to better understand the real differences between the regions themselves.

6. Disaggregate models: organizing the literature

6.1 Individual demand for transportation, accidents and their severity

When the unit of observation is the individual, and even if the structure of the problem remains the same as with aggregate data (description, explanation/forecasting/simulation of exposure to risk, and of frequency and severity of accidents), modeling must be adapted to account for relationships among individual behavior, demand for transportation, risk of accidents and their severity as well as the socio-economic, demographic and geographic factors, and those that influence the supply of transportation modes and determine their respective evolutions over time.

6.1.1. The tardy emergence of multiple levels

A. Disaggregate data and in-depth analysis of individual behavior

Choices of activities, including their spatial location and hourly programming, generate the transport modes and path choices, and consequently the number of trips and their distances, as well as the time spent by mode and by the hour (Chipman *et al.*, 1992).

These quantities[49] measure risk exposure because they characterize an individual's presence on, and usage intensity of, the network. The risk of accident and the severity that follows are thus dependent on the degree to which the transportation network is used. The literature reports two different effects associated with network usage intensity. If intensity increases the probability of accidents, it can also increase the level of awareness and the level of experience of the driver (a form of human capital associated with the use of transport networks), perhaps reducing the severity of accidents that occur.

B. Exposure, choice of mode included, since Warner (1962) or Abraham (1961)

There are a number of quantitative models mentioned in the literature that, since Warner (1962), have dealt with the individual demand for transportation[50]. The question of

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[49] We noted above that individual data could be categorical (the best quantifying tools then being Logit or Probit) or in the form of "counts" (the most appropriate tool being the Poisson specification). The "individual data" discussed here include both.

[50] Warner's Logit model of choice of transportation mode came later than Abraham's (1961) models of road itinerary choice, a fact seldom acknowledged. For a reminder and documented survey of the latter's random utility model derivations of the Probit and another choice model justification of Logit practice years before Domencich & McFadden (1975), see Gaudry & Quinet (2011).

transportation choices associated with the individual's activities is extensively covered in the literature (see for example, Ben-Akiva & Lerman (1985), McFadden (2001), Ortuzar & Willumsen (2002). For questions associated with the degree of usage of the transportation network, see Chipman *et al.* (1992), Kumapley & Fricker (1996) and Hivert (2002). These studies identify socio-economic and demographic factors (price, age, sex, household characteristics, *etc.*) that explain the time allocated to transportation and/or the distance driven.

C. The central role of pure accident frequency since Weber (1970, 1971)

Other quantitative models contribute to a better understanding of the factors that have an impact on an individual's probability of having an accident, this probability being considered independently of the severity of the accident.

Abdel-Aty *et al.* (1998) for example, study the relationship between the probability of accident (*i.e*, the risk of accident) and demographic characteristics such as the age and sex of drivers. Hu *et al.* (1998) study the risk of accident among older drivers. Boyer & Dionne (1986, 1987) examine the relationship between different types of automobile insurance choices and driver's behavior. This last matter raises moral hazard and adverse selection issues very difficult to analyze empirically, particularly with fixed, generally linear, functional forms [Gouriéroux (ch.12), 1999][51] that make it difficult to identify the anticipated risk[52] in the choice of insurance equation, especially if the accident equations are written without variables that measure exposure risk directly (Boyer *et al*., 1991; Dionne & Vanasse, 1996) and without distinguishing between categories of accident severity[53].

D. A first three-level DRAG-type structure in 1993

The double lack of realism just noted concerning the role of exposure and the heterogeneity of accidents (we noted above that severity is a critical dimension of the road safety problem) was commented on and solved by an exceptional three-level model by Bolduc's *et al.* (1993, 1994, 2012). Their first level explains **[OCC, DR],** the decision to drive and the distance driven.

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[51] In the context of the simultaneous determination of risk taking and actual risk described earlier, how are we to write a Line 4-type (Table 5) speed choice equation if the anticipated risk index **[A, G]*** depends on the same variables as those intervening elsewhere in {**[Other factors]**$_i^{cc}$} as sources of surprises? It becomes difficult to identify the endogenous variables unless one uses as anticipated (expected) risk index a measure such as EMI (Expected Maximum Insecurity) that makes it possible to then distinguish between the two roles of a given variable (Gaudry, 2006a). Clearly, if the EMI index is not a *logsum* but a simple linear function that depends on the same variables as those explaining frequency and severity, the distinction cannot be made and the two roles of each variable (as a determinant of expected risk in Line 4 and as a source of surprises in Lines 2-3) identified.

[52] As in the choice of speed discussed in the previous footnote, if the choice of insurance made by an individual depends on his anticipated risk of accident in Line 4 and, in Lines 2-3 on the same variables that explain this anticipated risk, how can one separate the two effects in the insurance choice equation without resorting to a *logsum* index like EMI?

[53] This approach goes barely further than Weber (1970, 1971) where two types of infractions are used to predict the frequency of accidents but where there is no knowledge of whether or not these individuals have accidents of the same severity (in fact, Shade & Heintzman (2004) have shown that these drivers have more severe accidents). Unfortunately, Bolduc *et al.*, (1993, 1994, 2012), who had opportunity to link bad driving to the severity of accidents by using the 4 variables that determine this behavior in their Table 13 by age group, fail to exploit this possibility in their models (of Table 11) by severity category (with material damage or with injuries) or by moment of the day (by day, in the evening or at night). Their results with respect to infractions to the Highway Code show a non-significant effect on the frequency of accidents similar to that found in Schade & Heintzman (2004), but show also that three other kinds of infractions have differentiated effects (sometimes null, sometimes even negative) on frequency by age group. It must be acknowledged that 29-variable equations may make it difficult to isolate factors that are more or less independent of each other. These factors are not comparable to those found in Krupp's (2005) cross-tables reproduced in Figure 7.B.

The other two levels are considered, first in a formulation of **[A]** independent from severity, and second in a combined in an explanation of frequency by severity level **[A/G]**. In terms of quantitative technique, the estimates are obtained by the first application of the Tobit-Poisson approach (Mullahy, 1986) to road safety data. In addition, results obtained with many other estimation procedures (*e.g.,* Poisson and Negative Binominal) are compared. A landmark.

Their estimates, unfortunately obtained with fixed mathematical forms, are based on data of a quality comparable to that used by previous authors, but with a greater number of variables. The set of variables includes, again after Weber (1970, 1971), past infractions to the Highway Code and to the Criminal Code, infractions sanctioned by the loss or temporary loss of the driver's license, and some medical condition restrictions applying to the driver's license. The authors' twin explanations of frequency independent from severity and per category of severity make use of variables belonging to all **PIMCYÂ** categories, including driving experience distinct from age, type of driving license, region and trip purpose.

Given the quality of the data and the number of levels used, it is certainly the most complete disaggregate model ever built. The Gaudry & Vernier (2000) model also has three levels **(A)-(G)-(CC)**, but focuses almost exclusively on the very fine characteristics of transportation infrastructure, road design, geometry and surface. In that sense, it is not as complete as Bolduc's model: in spite of its flexible mathematical form, it lacks information on drivers and their vehicles, both variables that should not be analyzed independently from the others. The results are therefore no doubt biased, this time due to another double lack of realism (on the characteristics of drivers and vehicles)! These examples are summarized in Table 10.

Table 10. Joint analyses of three out of four levels amongst [OCC, DR], A, G, and CC

	[OCC, DR], A, G, CC	**Model**	**Sample**	**Variables**	**Other**
Bolduc *et al.* (1993)	-OCC : driving -DR : kilometers and time -A/G : freq. of severity 1, 2	-Probit -OLS* -Tobit-Poisson	8160 drivers in 1985-1986 and their violations in 1980-83	-30 from 77 -36 from 77 -30 from 77	NLLS** Negative binomial
Gaudry Vernier (2000)	-A : all accidents -G : 3 severities -CC : moments of speed	-Logit -Logit -OLS*	-2 541 from 60 000 and -1 225 in 1991-95 -17 indices from 60 000	-32 from 80 -68 from 80 -6 from 80	-Box-Cox -Box-Cox -Box-Cox
* Ordinary Least Squares. ** Non-Linear Least Squares.					

E. Joint analysis combining exposure, frequency and other factors

Few, if any, studies with discrete data have analyzed the three dimensions of road safety (exposure, frequency and severity) from the driver's point of view as well as Bolduc *et al.,* (1993, 1994, 2012). Their modeling approach is generally accepted today even if the data required for it are considerable and if the taking of simultaneity into account is econometrically difficult. But it remains a first cut with only linear variables and some unanswered questions.

The authors' analysis of exposure is refined and explains both the decision to drive and the quantity of driving. In the analysis of accident frequency, their principal model explains frequency by group of drivers (4 groups in most cases) independently from the severity level, as in Weber (1970, 1971); but they also provide a competing analysis of frequency by severity level that fails to isolate fatal accidents from other injury accidents: the two categories considered are injury and material damage only accidents. In this competing analysis (in the first 2 columns of Table 9), 6 sign inversions occur related to age or amount of driving by age

group and trip purpose. Moreover, the use of the occurrence of the substitute type of accident to explain each one involves using a dependent variable for a substitute good as regressor for the first: it is like explaining coffee sales by the quantity of tea sold, and vice versa.

Clearly, this landmark formulation could benefit from further work to fully account for severity and to use flexible functional form on continuous variables, as in aggregate models. It should inspire practitioners of discrete data to develop system-wide analyses, including derivations of population values, a matter we shall return to.

F. Two (or less)-level models and the focus on the conditional severity of accidents

A large number of statistical models combining explanations and forecasts of "exposure-frequency" or "frequency-severity" can be found in the literature. Lourens *et al.*, (1999) for example, analyzed the demand for travel on roads simultaneously with the probability that accidents occur. Deyoung *et al.*, (1997) studied exposure to risk and the probability of accidents for California drivers who do not have a driver's license or who have lost it. And Ryan *et al.*, (1998) examined the influence of age on the exposure to risk and the probability that accidents occur.

Other authors concentrate on the severity of accidents, explaining those accidents in detail and linking them to various categories of the population. Farther, we will see that this refined literature is growing rapidly.

6.1.2. Analyzing exposure to risk

A. Distance driven or travel time?

Seen from the traveler's standpoint, the researcher should first look at the exposure to the risk of accident facing the driver. To account for aggregate national outcomes, this is a more important factor than the probability that accidents occur and perhaps more important even than their severity. The next step is to evaluate the driver's use of the transportation network. If the distance driven constitutes the main indicator of exposure, it is not the only one (see Chipman *et al.,* 1992). Time spent driving and the number of trips made are also equally viable measurements of exposure to risk. Nonetheless, most explanatory and forecasting models of the extent of the transportation network use focus on the distance driven, breaking it down by transportation mode, by type of road infrastructure or by socio-demographic category. Occasionally, models include a simultaneous study of the frequency of trips.

B. Mixing discrete and continuous variables

Statistical models use regression techniques to explain and/or forecast variables quantitatively. These can be continuous or truncated, correlated in time and space or independent, depending on the underlying assumptions and on the way disaggregated data are structured. When the frequency variable is used to measure exposure to risk, they become regression models of continuous and discrete variables.

C. Relating exposure to frequency

It must be noted that these approaches seem to be more closely linked to the analysis of demand for transportation (exposure) than to the analysis of road safety *per se*. But this is not always the case. For example, Chu *et al.*, (2004) looked at the way people cross a street using Stated Preference data. But, in fact, models designed to explain exposure often analyze the probability of accidents simultaneously. Modeled or not, exposure in naturally critical to the

explanation of the frequency of individual accidents and its absence, as noted above, basically invalidates many accident frequency models.

D. Heterogeneity and individual data

This is a crucial relationship. Short-term exposure to risk causes the frequency of accidents, but long-term exposure to risk may induce a change in the level of exposure to the risk of accidents. Nevertheless, at the individual level, these relationships do not carry the same weight as they do once they are aggregated. Values differ from one individual to another and cannot be easily aggregated. This heterogeneity is an important factor in the design and evaluation of transportation policies that target specific socio-economic segments of the population.

6.1.3. Analyzing the frequency of accidents

A. From exposure to other factors

In Bortkiewicz's approach of 1898, completed by Weber in 1970-1971, and which constitutes the disaggregate counterpart of Smeed's work of 1949, the analysis of an individual's frequency of accidents during a certain time period is quantitatively defined as the identification, specification and estimation of the distribution of the probability of the number of accidents during that period (*e.g.* Shankar *et al*., 2003). Representative examples are found in Table 11.

Table 11. Representative analyses of the frequency of accidents since 1970

	Accidents	Model	Sample	DR, A, G	P	I	M	C	Y	Â	Form
Weber (1970)	All	Poisson	148 000, California, 1963	5 variables including DR_t, A_{t-1} and C_{t-1}							Linear
Boyer *et al.* (1988)	All	Probit	20 027 drivers, Quebec, 1980-82	53 variables including A_{t-1} et C_{t-1}							Linear
Fosser *et al.* (1999)	Bodily injury or liable	Logit	211 731, Norway, 1992-94	42 variables including DR_t, vehicle age (5), sex (1) of owner (17) and residence (19)							Linear
Vernier (1999)	All	Logit	2 541 on 50 000 road sections, France 1991-95	32 variables including DR_t, speed and 30 road infrastructure characteristics							Box-Cox

Researchers can easily choose to model the probability of accidents only over a given time period, or over many. In all cases however, models seek to identify the factors that affect the statistical distribution. Studies have shown that the level of exposure to risk is a significant factor, thus a *necessary* one, but not a sufficient one, as demonstrated by Weber's model, probably the most complete of all models listed in Table 11. No other model has used as many categories of relevant variables as Weber, the seminal, but often unrecognized, baseline to measure progress in discrete road accident analysis in the last 40 years.

B. Actual exposure, a necessary but insufficient determinant of frequency

Among factors of importance beyond exposure, the mode of transportation (car, motorized two-wheelers, non-motorized two-wheelers, busses, *etc*.) and the social and demographic characteristics of the individual (age, sex, *etc*.) matter. And, as mentioned previously, many authors (*e.g.* Boyer *et al*., 1988) imitating Weber's (1970, 1971) approach without making due reference to his work, have included variables such as the driver's past accident [A_{t-1}] and infraction [C_{t-1}] records. Often, such models have more explanatory variables than Weber's but unfortunately fail to include the measure of exposure required for progress in the

explanation of accident frequency, using instead for this purpose auxiliary dummy variables per age and region, in the manner of actuaries. These categorical variables, poor substitutes for continuous observed exposure, can bias the estimated coefficients of other variables, as we now discuss further.

C. Dummies en lieu of actual exposure and resulting frequency estimation bias

The proper representation of exposure in an explanation of accidents during a particular year, such as 1982, is indeed critical to the realism and unbiased estimates. Studies completed in Norway on the frequency of accidents and the age of the vehicle (Fosser, 1992; Fosser & Christensen, 1998; Fosser *et al.*, 1999) have shown that the annual frequency of accidents cannot be considered independent from (orthogonal to) the exposure to risk. The same has been shown by Bolduc *et al.* (1993, 1994, 2012) working with data similar to those used by Boyer's *et al.* (1988), but for the 1985-1986 year.

These studies carried out by Fosser and Bolduc are strictly econometric in nature and as such differ from (partly or fully) actuarial models that rely on categorical dummy variables as measures of exposure. The latter are safe enough for forecasting but are also typically obscure, and not only biased. Breaking an annual cross-sectional sample down into categories by age and region amounts to using monthly auxiliary dummy variables in a monthly time series model. It reproduces the phenomenon but does not explain it. The bias in coefficient estimates arises from the fact that the "actuarial" dummy variables are never orthogonal to the remaining proper explanatory variables.

It is then without surprise that playing with various distributions in the estimation of a frequency model, as in Boyer *et al.* (1990), turns out to yield very little: modifying the distributional assumptions cannot in a model compensate for the lack of valid exposure variables or for the use of supposedly linear "regression components", both at the center of any empirical accident frequency model. The results obtained by Fosser, Bolduc and their co-authors have established the crucial role played by the proper exposure variable and models of the DRAG family have cast doubts on all results based on supposedly *a priori* fixed mathematical forms for all variables, and notably for the measure of exposure.

6.1.4. The detailed analysis of severity, a recent endeavour

Derived from countless reports and databases on road accidents, statistical models applied to the analysis of the severity of accidents are very numerous. Table 12 lists the most representative, among which Kockelman & Kweon, (2001), Zhang *et al.*, (2000), Farmer *et al.*, (1997) and O'Donnel & Connor (1996) are to be found. Their objective is to explain the variations in the distribution of the severity of accidents by the demographic characteristics of the persons injured, by the spatialization of the accident and by an elaborate set of fine details describing the environment [E_{av}] where the accident took place. All this information is derived from databases providing detailed information on individual accidents [A]. We note that none of the examples of Table 12 yet uses the notion of *panel*, even if multiple successive cross-sections of observations on the same individuals are actually available and used.

A. The idea of the "fine environment" of individual accidents

Latent variable models, whether of ordered or unordered choices, such as Probit, Logit and GEV — (see Gourieroux (1989) and Train (2003, 2007) for a theoretical and algebraic description of their requirements and properties) — are probabilistic approaches to the identification of factors having significant effects on the level of severity of accidents: location (at an intersection or in a specific lane, *etc.),* configuration (number of cars, type,

direction of traffic, etc.) of the accident (e.g. Clifton *et al.*, 2009), age and sex of the victims, weather conditions, type of lighting used on that particular section of the road or highway, use of safety equipment, *etc*.

Table 12. Representative analyses of the conditional severity of accidents

Authors	Model	Variables				
		M	**C**	**I**	**E$_{nv}$**	**A**
Farmer *et al.* (1997)	Multinomial Logit	Yes	Yes	–	–	Yes
O'Donnell & Connor (1996)	Ordered Probit and Logit	Yes	Yes	–	–	Yes
Khattak *et al.* (1998)	Ordered Probit and dichotomous Probit	–	–	–	Yes	–
Renski *et al.* (1999)	Ordered Probit	–	–	Yes	–	–
Chang & Mannering (1999)	Nested Logit	Yes	Yes	Yes	Yes	Yes
Krull *et al.* (2000)	Multinomial Logit	Yes	Yes	Yes	–	Yes
Al-Ghamdi (2002)	Multinomial Logit	–	Yes	Yes	Yes	Yes
Kockelman & Kweon (2001)	Ordered Probit	Yes	Yes	Yes	–	Yes
Bedard *et al.* (2002)	Multivariate Logit	Yes	Yes	–	–	Yes
Dissanayake & Lu (2002)	Multinomial Logit	Yes	–	Yes	Yes	–
Ulfarsson & Mannering (2004)	Multinomial Logit	Yes	Yes	Yes	Yes	Yes
Kweon & Kockelman (2002)	Ordered Probit and Poisson	Yes	Yes	–	–	–
Toy & Hammitt (2003)	Multinomial Logit	Yes	Yes	–	–	Yes
Khattak & Rocha (2003)	Ordered Logit	Yes	Yes	–	–	Yes
Wang & Kockelman (2005)	Heteroskdastic Logit	Yes	Yes	Yes	Yes	–
Holdridge *et al.* (2005)	Nested Logit	Yes	Yes	Yes	Yes	Yes
Lapparent (2005)	Beta-Binomial	Yes	–	Yes	Yes	Yes
Lapparent (2006)	Multinomial-Dirichlet	Yes	Yes	Yes	Yes	Yes
Eluru & Bhat (2007)	Bivariate Ordered Logit (mixed distr.)	Yes	Yes	Yes	Yes	Yes
Lapparent (2008)	Bivariate Ordered Probit	Yes	Yes	Yes	Yes	Yes

C: driver characteristics; **M**: vehicle characteristics; **I**: infrastructure characteristics; **E$_{nv}$**: environnemental characteristics ; **A**: accident characteristics.

B. The observed levels of severity

The true level of severity of an accident is considered as unobserved and approximated by a discrete variable generally obtaining a value based on interval values taken by the latent variable. Most applications rely on a four-level classification of the severity of accidents: material damage, light injuries, serious injuries and death (see Figure 13). However, some databases use less common categories.

Figure 13. Conventional link between degree of severity and category of severity
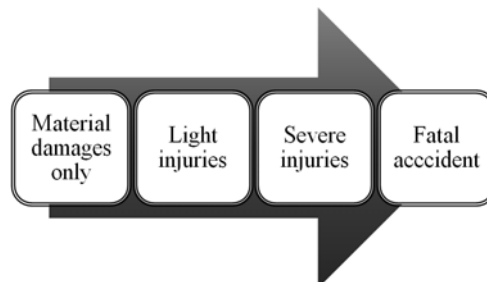
C. Severity and ordered measurements

When categories of severity are ordered and/or are very detailed — based on a combination of many factors accounting for severity — the statistical models are either polytomous unordered discrete variable models (eventually multidimensional) or models with discrete ordered polytomous variables. An example of the first case would be the combination of the level of severity with an indicator of the use of safety equipment, or the level of severity multiplied by a dummy variable indicating the degree of responsibility of the driver. An example of the second case could be a distinction between bodily injury and material damage events, each based on a latent continuous ordinal variable, with some recognition of the possibility that they could be correlated. For more information on unordered discrete variable models, see Ulfarsson & Mannering (2004) or Kim *et al.*, (2007). There are thus many ways to define the severity of accidents.

D. Severity and simultaneous estimation

Recently, equation systems have progressively been designed to account for simultaneity in the determination of many variables that explain the level of severity of an accident. The idea is to account for the drivers' safety and care decisions (the set **[CC$_i$]** of line 4 in Table 5) in explaining the severity (in line 2-3 of Table 5), and sometimes to account for the reverse effect of anticipated severity on the care decision itself. For instance, Gaudry & Vernier (2000) *simultaneously* determine speed, (frequency) and severity of accidents on certain French road segments in this way.

Eluru & Bhat (2007) and Lapparent (2008) for their part have suggested that the factors influencing the use of safety belts and the severity of accidents could be studied simultaneously — to account for the fact that, even if the decision to buckle up is a personal one, it has a direct effect on the degree of severity of an accident. The models suggested by these authors are bi-dimensional. Their object of study is the same, but statistical specifications differ according to the way in which these relationships are defined.

6.1.5. Other approaches and unsolved problems

A. Empirical typologies

There are numerous other approaches seeking to model the distribution of the probability of certain layouts of accident scenes and the probability of levels of severity derived from the analysis of a plethora of accident reports. For example, it should be possible to build a statistical model of the type of collision, of the number of cars involved (eventually by type), of the number of victims and of the severity of their injuries. This type of model allows for the establishment of a measurement of the rate of occurrence (in relation to the total number of accidents) of certain types of accidents and of levels of severity of the injuries suffered by the drivers involved in these accidents, based on a typology of accidents (to be defined according to the need and the precision sought).

The results should provide a definition of the types of accidents causing high levels of severity and consequently lead to practical recommendations designed to decrease their number. Precise and detailed reports of individual accidents are a gold mine of information offering vast modeling opportunities and contributing to a better understanding of the typology and severity of road accidents.

B. Defining the time period and simultaneity

Some approaches worth mentioning are seldom found in the literature on road safety performance models. These are models that examine simultaneously the frequency and the severity of accidents linked to an individual driver *over a given time period* instead of at a given moment *t* in time (in which case the exposure to risk is predetermined). Simultaneous analysis can only be applied to other factors such as behavior at the wheel, frequency and severity. However the data required are scarce and disparate.

6.2. From microscopic to macroscopic: how to aggregate

In order to assess the effectiveness of newly implemented road safety regulations, some disaggregate results must be generalized. It is a justifiable requirement that allows policy makers to evaluate the global effect of the policies while, at the same time, taking into account the finer details of the information collected. As a corollary, the consequence of this generalization is that the researcher has to choose a reference aggregate: will it be a social group, a geographic zone, a transportation network or transportation modes?

The issue of data aggregation was raised early on in discrete demand analysis (Kulash *et al.*, 1972) and solved practically as the choice of mode literature flourished after Domencich & McFadden (1975). The issue arose as that of the values attributable to given population but derived from a sample of modeled "representative individuals". Difficult questions of consistent aggregation from the microeconomic to the macroeconomic were ignored: the problem was simply to derive aggregates from functions estimated from discrete data, and not to find aggregated functions of characteristics compatible with the individual ones[54]. Demand models were of course exposure models, but driving risk was not on the menu.

6.2.1. Demand independent from accident risk

In the literature, we have in fact found no discrete choice demand or mode choice model where the anticipated risk of an accident is taken into account when the driver *decides to take on the risk of driving* (the exposure risk). It can be said that a modeling approach seeking to derive total values for a given population is still in its infancy, in particular with respect to the frequency of accidents and their severity.

The first models of regional or urban values derived from individual results are promising, as in the UrbanSim project (Waddell *et al.*, 2003). We hope that this approach will be applied to national road safety performance statistics in the future. This would require accounting for driving risk in the very structure of the models, as well as important structural extensions.

6.2.2. Criteria and scale of aggregation

How should one aggregate? By combining a number of aggregating criteria? Elvik (1988) has already noted that it is difficult to define indicators of road safety when using aggregates of individual data from socio-demographic groups: the sample of observed accidents has to be redressed, *i.e.* corrected, to take into account missing information, particularly in the case of accidents with material damage only and light injuries. Thomas (1996), for her part, studied the aggregation of spatial information in order to model road safety performance itself.

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[54] These questions of compatibility between aggregates and micro-relationships are summarized in many articles (*e.g.*, Fortin, 1989).

There is a wide range of possibilities for data aggregation, from individual data to the national level (or higher even). All levels of observation allow for the analysis of factors having an impact on road safety. These approaches are called *mesoscopic*. They rely on the design of a particular view of the problem and on the choice and gathering of semi-aggregated or semi-disaggregated data. The analysis of the exposure to risk and the analysis of the severity of accidents are themselves based on levels of observation and on criteria that are not specific to the individuals or to a country. The most commonly used levels of observation are: the different modes of transportation, the age groups, sex, the transportation network (with subcategories by speed, status or segment characteristics, regions, States (USA), Departments (France) or Provinces (Canada), metropolitan areas and other geographic and/or administrative divisions).

6.2.3. Is aggregation part of the definition of a discrete model?

This is a fundamental question: where do we draw the line between a quantitative model based on disaggregate data and a quantitative model based on aggregate data? When does a model become formally disaggregate? It is in the way the aggregation is done, *i.e.*, when values attributed to a population are derived from individual data?

It may be said that deriving values for a whole population is in fact part of a complete disaggregate model. This is what Bolduc *et al*., (1993, 1994. 2012) did by clarifying their procedure in their title "a disaggregated tool…" and including as part of the model a *simulator*. To do otherwise would amount to estimating equations for a particular group without being able to calculate the elasticities of the aggregates. Assessing road safety policy and regulation thus requires that a disaggregated model come with a built-in "simulator of aggregates".

6.3. Spatialization of the data: is the network the solution?

When the unit of observation is a network segment, the modeler has the option of developing a model component to forecast the generation and location of accidents (by mode and level of severity) and to integrate this module to components accounting for the demand for transport and its assignment to the network.

The purpose is to make spatio-temporal analyses of the variation of accidents by type occurring on the network. How many accidents? Where did they take place? Has there been a change over time?

6.3.1. Frequency of accidents

A. Frequency and infrastructure

One can study at the link level the relation between their characteristics, demand and accidents. This is a commonly used approach that aims to explain the impact of infrastructure on the number of accidents given a specific demand for transport. This method allows for the identification of the factors on a road segment that have accident potential (also called black spots or black zones). Understanding the relationship between the frequency of accidents, traffic, and particular road infrastructure characteristics (vertical or horizontal geometry, number of lanes, direction of the flow of traffic, surfaces, fixings, road signs and markings, speed limits, *etc*.) has always been of interest to the community of researchers. McGuigan (1981) long ago suggested that it might be possible to identify dangerous sites using this approach. We have noted above in section 4.1.2 and Table 5 that the formulation of the

problem is modified in a simultaneous equations formulation linking driving care **[CC]** and accident frequency and severity **[A , G]**.

It is also the case that, to the extent that accidents are largely random, or that the regression component of the accident model only explains a relatively small part of sample variance, extreme care is warranted in the analysis of interventions to correct "black spots" because the extremely atypical (high) values of the count tends to "revert to the mean", *i.e.* change over time by themselves towards their mean value independently from interventions: it is therefore difficult to establish the effectiveness of measures to suppress black spots to the extent that they are so variable due to unaccounted for random reasons (Hauer, 1996). With or without the intervention, the atypical random value most likely won't exist in the next period and the safety performance of the link will improve.

B. Frequency and data counts

This type of modeling requires count data. From Poisson's (1837) original approach right up to the recent synthesis by Cameron & Trivedi (1998) and the work of Munkin & Trivedi (1999), the theoretical development of statistical models based on counts has progressed in giant steps. Nowadays, count data models integrate refinements such as heterogeneity, heteroskedasticity, selection biases, truncation, simultaneity biases, endogeneity biases, spatial correlation, temporal correlation, *etc*. The study of black spots triggered new count data formulations (and/or the modification of old ones) using new data sets, sometimes long after the availability of the improved technique. There are many examples of this type of work in the literature.

C. From Poisson to Bayes

Most mathematical models use the Poisson distribution and its extensions (un-observed heterogeneity, temporal auto-correlations), sometimes within a multi-dimensional framework but seldom with spatial correlation.

The Poisson model and the Negative Binomial model remain the dominant quantitative tools for research done in this field. Applications focus mainly on road accidents involving motorized vehicles (*e.g*., Miaou, 1994; Persaud, 1994; Shankar *et al*., 1995; Hamaoka *et al*., 1999; Hauer, 2001). Similarly, most methods used to estimate accidents are based on the classic statistical principles of inference. However, the number of approaches based on a Bayesian paradigm is increasing (Persaud & Kazakov, 1994; Persaud *et al.,* 1999; Bossche *et al*., 2003).

6.3.2. The location of accidents

A. Frequency and spatialization

One of the consequences of attempting to explain the frequency of accidents on specific road segments or intersections on a transportation network is the need to spatialize the accidents. This means integrating the spatial dimension to the other elements that define and characterize the network. This is not a novel approach, but with the help of very precise recent information and communications technologies, collecting statistical data has had renewed success.

In the last 15 years, we have witnessed an immense increase in the quantity and quality of the information on transportation networks. As a result, the methods used to analyze these new

data (including traditional modeling) have also improved enormously. This improvement becomes obvious when we compare present with past work, for example, those of Deacon *et al.*, (1975), Hauer & Persaud (1984) and Hauer (1986), to the recent studies of Schlütler *et al.*, (1997), Heydecker & Wu (2001) or Flahaut *et al.*, (2002). These greatly improved means and methods are used for two types of analyses: exploratory (or descriptive) and statistical (or explanatory).

B. Descriptive analysis

An example of the first type of analysis worth mentioning is Concerto, a French application developed for the official French statistical office responsible for road safety statistics (ONISR). It processes the data on accidents for the benefit of local or national research projects on the subject. It categorizes accidents on the basis of given criteria, illustrates the results on maps, identifies itineraries and allows for subjacent statistical studies such as indicators of safety, multi-factor analyses, pre and post adjustment assessments, identification of dangerous zones, development of trends, *etc*. Concerto's main purpose was to track the evolution of accidents over time and provide decision-makers with information relevant to urban planning and road safety. The data collected is fed into a GPS system (*Système d'informations Géographiques* (S.I.G.)).

As far as we know, Concerto does not contain an explanatory statistical model, nor is there a built-in underlying predictive model. The data are analyzed *a posteriori* and projections are made based on an interpretation of variables the relationships and dynamics of which have not been explicitly modeled. In other countries where this type of data gathering is possible, similar computer programs and approaches have become very popular.

C. Explanatory analysis

Explanatory or predictive models (*e.g*. Maher & Summersgill, 1996) have also evolved. In the last few years, a few models based on generalizations of parametric regression models using count data have been developed. Be they Poisson or not and multi-dimensional or not, they occasionally include non-observed heterogeneity or temporal correlation (*e.g*. Ulfarsson & Shankar, 2003) but only rarely spatial correlation.

This is very surprising, given that road segments are obviously linked together and that an accident on one segment can affect the whole transportation network. Nonetheless, these models help explain and predict the location of certain types of accidents on a network according to the distribution of traffic and the characteristics of the network, even if their handling of spatial correlation of residuals leaves much to be desired.

6.3.3. Taking road safety into account in policy evaluation

A. The spatial dimension in demand and accident analysis

The merging of the disaggregate approach for spatializing accidents to a system that forecasts and simulates the demand for transport has not yet been effected. It would however constitute a step towards explaining the relationship between a higher level of demand for transportation and a higher risk of accidents. It would also help quantify the impact of certain policies (fares, infrastructure, *etc*.).

B. Traffic flow

The occurrence of accidents and their location depend on the flow of traffic on the network. This flow stems from the aggregates of origin-destination movements. This demand is distributed over itineraries and modes of transportation. As a result, any policy affecting one mode can potentially affect the location of accidents on another mode. And any policy having an effect on the quantity or the variety of the supply of transportation affects the spatial distribution of accidents and their level of severity.

One can easily imagine the effect of the introduction of a policy promoting public transit. An increase in the use of public transportation would decrease the load on the road network. The remaining traffic would move faster, particularly on certain segments. Given a lighter load, increased speed and some physical characteristics of road segments, the probability of certain types of accidents occurring, their distribution, location on the network and level of severity would also change. However, researchers can only evaluate the impact of the policy *a posteriori*, unless they possess *ex-ante* the tools and data necessary to predict and quantify the shifts from one mode of transport to another, not the least of which is a shift to more dangerous two-wheel vehicles.

C. The road segment as the observation unit

Modelers have a unit that is common to both forecasting systems when choosing a segment of the transportation network (even a rail segment) as unit of study, the network being considered as their particular spatial structuration: the two could be merged. For example, a predictive model for the demand and distribution of traffic in a specific area (a classical 4-step model) could be merged with a predictive model of the probability and spatialization of accidents in the same area.

6.4. References

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Part 3. Multivariate road safety models: future research orientations and current use to forecast performance

7. Concern for user classes: top down or bottom up?

What should the next step in road safety performance modeling be? The basic distinction between aggregate and disaggregate streams will likely continue for a long time: the merger of the two approaches is beyond the realm of current possibilities, even assuming that any safety issue can be addressed with either kind of data, which is very far from certain. Think of critical problems, such as that of the structure of the market over time and that of "the bottom of the barrel".

For instance, could "The Mystery of 1972-1973" mentioned in Section 3.2 of Part 1 ever be studied with panels of discrete data combined with credible aggregators to national values in order to explain the location of the maximum in each country (of the 30 listed in Table 4, 4 maxima in 1970, 10 in 1972, 3 in 1973, *etc.*)? Similarly, if the downward trend in those countries that are past their maximum in fatalities is slowing now down, or even reversing itself, how can panels help to predict an asymptote or an eventual turning point?

Conversely, how could the intrinsic dangerousness of classes of individuals identified by Weber's use of past offense records, and shown to be independent from their age and sex by the extraordinary German data of Figure 7.B of Part 1, ever be studied with aggregate data? How could one avoid using discrete data to design (and evaluate) laws and penalties in order to target problem groups instead of everybody, or even the average individual?

Despite the difficulty of, and perhaps the unwise hope for, a methodological unification of the field, a few current concerns shared by both traditions deserve to be mentioned along with more fragile hypotheses on the future of modeling[55], particularly with respect to forecasting. The first such development is the growing interest in classes of users, mentioned rather in passing in the previous two Parts of this state-of-the-art. Clearly, classes of victims change in relative importance over time and user behavior is heterogeneous in specific ways that should matter for the understanding of the quantity and evolution of national totals themselves.

7.1. The top-down ways are many

7.1.1. Should totals be disaggregated into user classes?

If we try to explain the 1972-1973 "mystery peak" in the death toll on roads, an issue of particular importance to countries where this toll is still rising, breaking down the toll by category will not necessarily help us find a causal relationship. In France for example, the only user category that did not peak in 1972, together with pedestrians and car drivers, is cyclists (see Figure 14, from Orselli, 2004).

A. Total behavior and behavior of the components

How do sub-totals of fatalities evolve for the 12 other countries than France (listed in Table 4) sharing with France the moment[56] of their maximum in 1972-1973? This question has not been studied, but one can look at some particular cases, like The Netherlands (which peaked

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[55] The statistical methods of econometrics applied to transport will continue to improve. At this point in time though, we have not seen or heard of a statistical or econometric method that has been developed *specifically* for road accident analysis in the way the Logit surge has been driven by the study of mode choice since 1975.

[56] As in most countries the yearly maximum is in August, countries that had their yearly maximum of fatalities in a certain year, such as 1972, probably had their actual maximum in the same month.

in 1972 as well), in Figure 15 where the breakdown by user category is similar to that for France. Pedestrian deaths peaked in 1972-1973 in both countries, but the similarity ends there. The number of cyclist[57] deaths peaked in 1972-1973 in the Netherlands but not in France, and the number of light utility vehicle deaths peaked in 1972-1973 in France but did so years before, between 1965 and 1969, in the Netherlands.

Figure 14. Breakdown of non-automobile casualties, France, 1957-2004
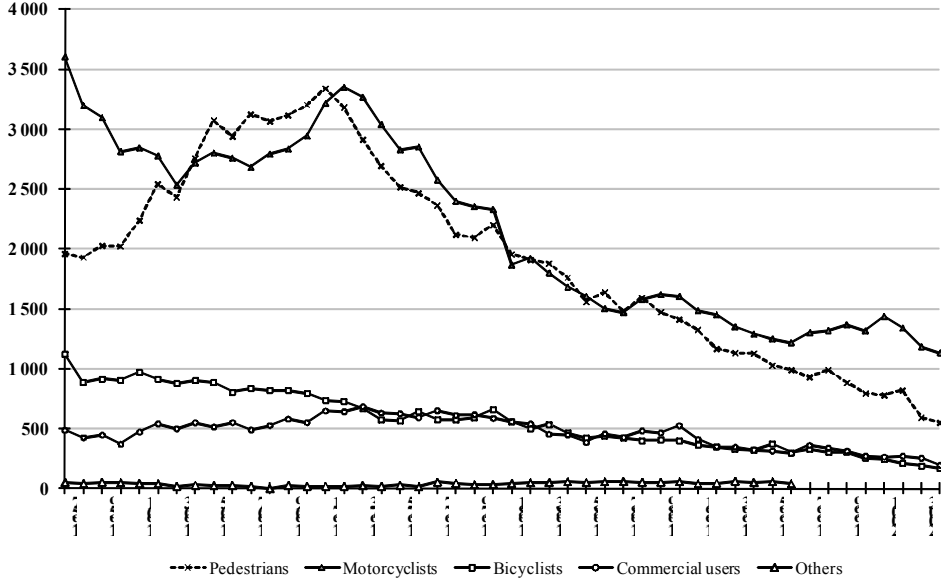
Figure 15. Breakdown on non-automobile casualties, The Netherlands, 1950-2005
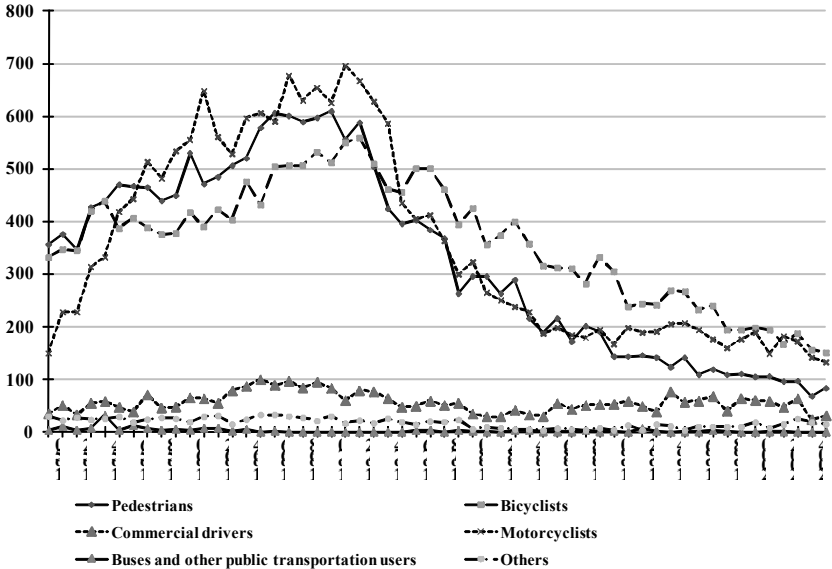
Thus, a simultaneous global maximum is not a proof that user categories behave the same way as the totals. A multi-national modeling analysis might help us better understand the 1972-1973 phenomenon, but its potential results can hardly be relied on. Figures 14 and 15 illustrate the need for disaggregated analyses of user categories but do not suggest any way of doing it.

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[57] Bicycles are commonly used in the Netherlands, often as a means of transport to go to work.

B. How to analyze the components?

There are basically two ways of analyzing the time series of data for user categories. First, one could directly formulate an equation for each category; second, one can try to explain category shares. In this latter case, the probable approach would be "quasi-direct", with the number of victims by category expressed as the product of a model explaining all victims by another explaining their shares or probabilities of occurrence.

With the first option, how could one explain and forecast the evolution of each component separately? For instance, we know that the number of victims of motorized two-wheel crashes depends on the size of the fleet, as Figure 16 shows with 56 observations in the Netherlands[58].

Figure 16. Motorized two-wheels: fleet size and casualties, The Netherlands, 1950-2005 (Stipdonk, 2007)

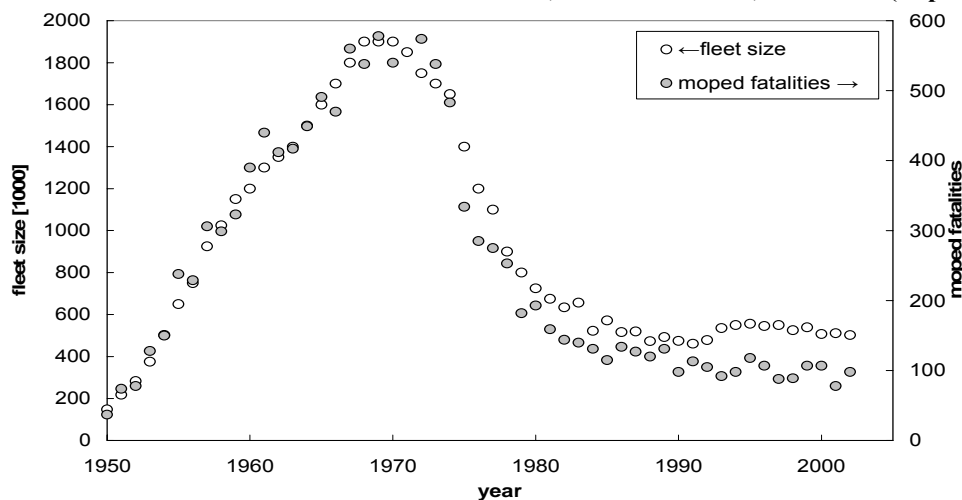But then, how can one distinguish the influence on each victim category of its own fleet from that of other fleets? In the same way, how does regulation, often designed for one specific category of road users influence outcomes for other categories? If all variables are used in all equations, it becomes difficult to separate what influences mostly the total from what affects primarily a given category, as the second option better allows for by its very structure.

The "Quasi-direct format" is commonly used in the analysis of transport demand. It makes it possible to reassign certain variables (*e.g.* the gradual implementation of the safety helmet regulation[59]) from the model part explaining the total number of victims (where their effect is barely perceptible) to that explaining the shares, where fine effects on sub-categories can more easily be identified. And it also makes it possible to have certain variables play distinct roles in the explanation of totals and shares. How could that be?

C. The Quasi-Direct-Format (QDF)

To illustrate why this approach could better serve the analysis of categories of accidents that the direct one, let us take a close look at its formulation in studies of demand for transport. It multiplies an explanatory equation of the demand for all modes of transportation (T_{ij}) by another model, Logit or other, explaining the mode choice p_{ijm}, as follows:

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[58] It appears that there was a 40% increase in registration of motorized two-wheels in Paris from 2002 to 2007. Given the relationship between accidents and size of fleet seen in the Netherlands, we can expect a larger number of victims in this category in France as well.

[59] Safety helmet regulation was introduced gradually in France. In June 1973, it applied to motorcycles and outside city limits, and to drivers only. The regulation was further extended in 1975, 1976 and 1979.

(10)
$$T_{ij_m} = T_{ij} p_{ij_m}$$

where T_{ijm} is the flow between i and j by mode m, formulated explicitly for all origin-destination flow from i to j and mode m :

(11)
$$T_{ij,m} = \left\{ f(A_c, A_d, U_{ij}) \right\} \left\{ U_{ij,m} / \sum_m U_{ij,m} \right\}, \quad m = 1,...,M, \quad ,$$

where U_{ij} , a global utility index of all modes, couples the two original models and captures the induction effect as follows:

(12)
$$U_{ij} = \sum_m U_{ij,m}$$

a formulation that varies with the chosen share model, for example, a linear Logit:

(13)
$$U_{ijm} = \exp \left[\sum_k \beta_k X_{ijmk} \right]$$

As a result, when a network variable X_{mk} changes, the elasticity of the total demand per mode with respect to the change in this variable can be broken down into two additive parts: one on the modal choice and the other on the induction. This breakdown results from (10) being the product of models: the elasticity of the total number per mode is thus written as the sum of the elasticities of the dependent variables of each model used, each written $\eta(y, X_k)$:

(14) $[\eta$ Demand for Mode $m] = [\eta$ Total Demand for all modes$] + [\eta$ Share of Mode $m]$,

i.e. neglecting the modal index to simplify:

(15)
$$\eta(T_m, X_k) = \eta(T, X_k) + \eta(p_m, X_k),$$

or even more explicitly as in (16).

The QDF usually implies that any variable X_k can appear not only in the share model, and as a result in the Utility index U_{ij} if the model is coupled, but also in the actual model of total level. For instance, income can affect the choice of mode AND the overall level of mobility. As a result, (15) is written at length as follows:

(16)
$$\eta(T_m, X_k) = \eta(T, X_k) + \eta(T, U) \bullet \eta(U, X_k) + \eta(p_m, X_k)$$

a sum where the right hand side can easily be interpreted: the first two terms are induction elasticities and the third is the elasticity of the modal shift. In most models, only socio-economic variables appear in the first and third term; the network variables appear in the two others. It is also possible to combine aggregate-type models of levels with models of shares or of probabilities; a utility program (Liem & Gaudry, 1994, 1998) calculates all terms used in (16).

QDF may be used whenever the combination of the explanation of the total and that of its share is preferable to building models with as many levels as there are alternatives. For example, if we explain the demand for public transportation by mode of payment, it is more

difficult to design a model with equations for each transport entitlement (cash, individual ticket, booklet, special card, etc.)[60], than it is to combine a model of choice of title with a model of demand for public transportation based on the utility of all modes of payment[61].

The application of the QDF structure to accidents remains to be formulated in detail and the explanation of accident shares by category will not be simple either. For example, why did the share of casualties associated with motorized two-wheels increase in France (from 20.6% in 1972 to 23.1% in 2006) but decrease in the Netherlands over roughly the same period (from 22.0% in 1971 to 17.7% in 2005), in both cases, after their peaks? Is it pure happenstance?

7.1.2. Is the detailed network level the solution?

Explaining accidents at the detailed network level may be an interesting approach. Different types of infrastructure do show different performances. For instance, the French casualty rates illustrated in Figure 17 (Rollin, 2004) indicate that, in 2006, 75.24% of the 4,709 deaths resulted from accidents on secondary and local roads (the rest were on highways and national roads).

However, when explaining the demand (and the exposure risk) from *i* to *j*, one is led to think that aggregating by type of road network has its limits. Indeed, itineraries generally combine segments of different networks. This means that socio-economic factors and distinctions such as urban *vs* rural may provide more relevant information than the type of itinerary or the type of road segment used. Segments will help define the risk associated with one itinerary from *i* to *j* but will not constitute an aggregation criterion sufficient to meet the requirements of behavioral national road safety models. The reason is that compiled totals will be constructed only from the characteristics of individuals and their distributions and merely be *derived* for the road segments chosen by these individuals. In a behavioral model, individuals make choices but roads do not, even if they may influence the choices people make, and notably their exposure decision due to their link-specific risk characteristics.

Figure 17. Casualty rate per billion car-km and by network, France, 1990-2004

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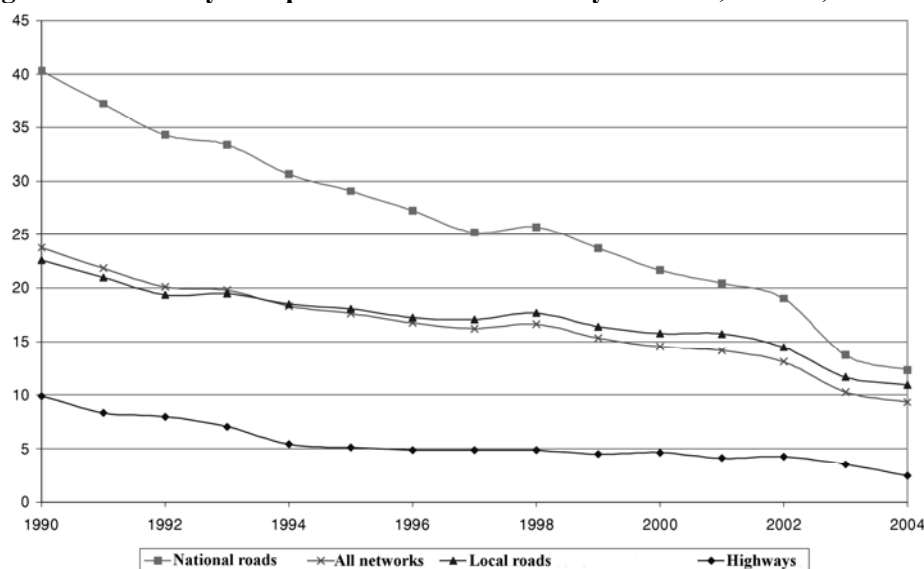
[60] As Gilbert & Jalilian (1989) did with limited success for London.
[61] As Laferrière (1997) did simply for Montreal and Transek (2006) did more elaborately for Göteborg.

The fundamental difference in units of measurement — sometimes referred to as "dimensions" — between demand (from i to j) and road flows (on segments s) remains decisive. Naturally, studying the flow of traffic on segments is useful, for example to calculate specific risk indicators for itineraries composed of segments varying in their risk generating properties.

7.1.3. The environment: is the *milieu* the solution?

Behavioral aggregates show marked differences between urban and non-urban areas in all countries: Figures 18 and 19 illustrate the case for Algeria. At first sight, the behavior of the two monthly series in Figure 18 may give the impression that the urban and rural fluctuations are close enough and move together, but their ratio, found in Figure 19, reveals actually very different time profiles of the underlying component series. When closely examined, Figure 19 exhibits some cyclical behavior of the ratio, as well as deeper differences during the enhanced road security measures (say from 1991 until 1995) associated with the civil war, such as army road block intensity across the various networks, *etc*.

Figure 18. Monthly rural and urban casualties, Algeria 1970-2006 (Himouri & Gaudry, 2008)
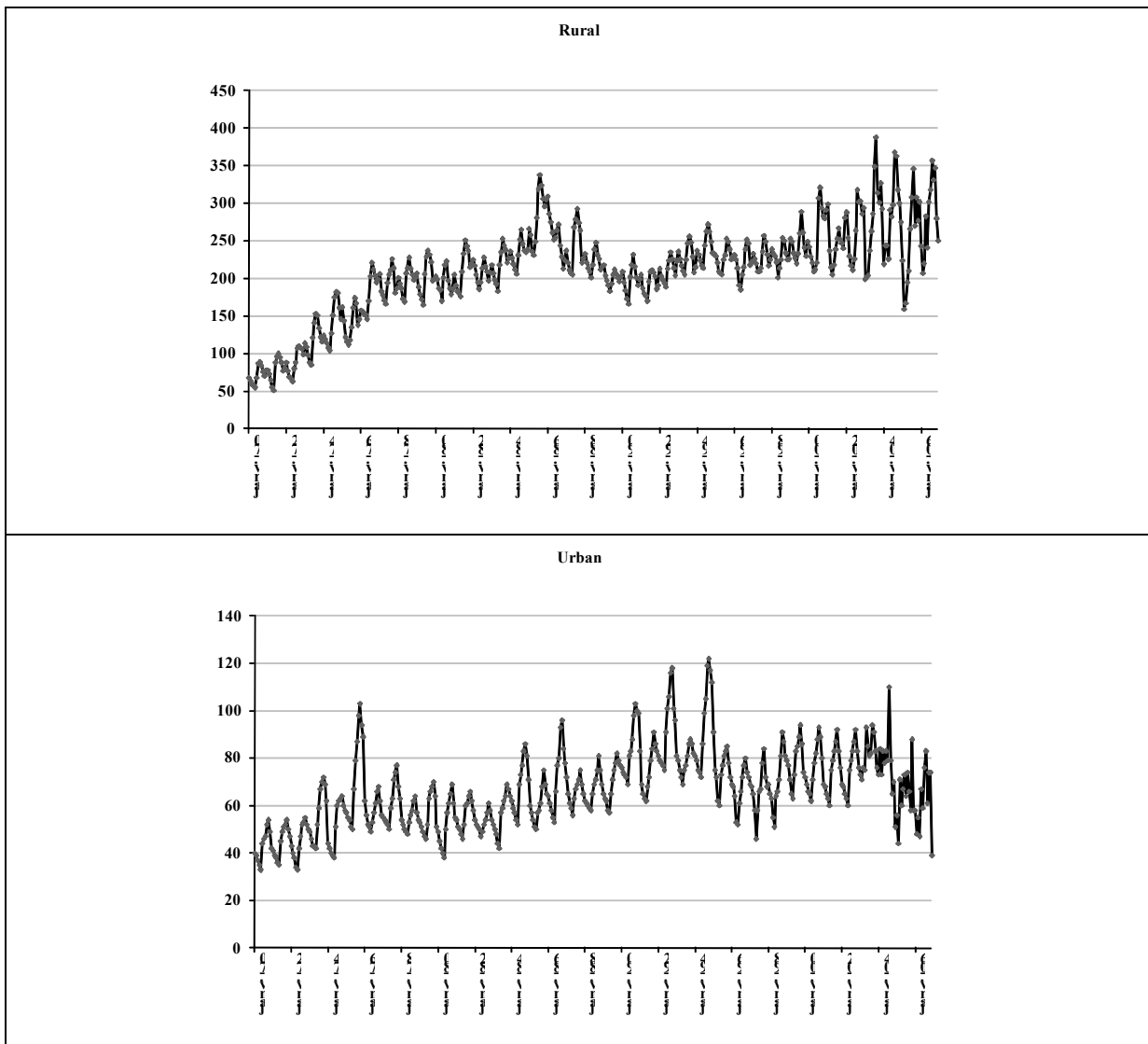
Hopefully, the distinction between urban and non-urban areas will be studied further, and not only for Algeria. It implies more than differences in levels of traffic, notwithstanding the increasing importance of congestion in urban areas caused by speed limits and restrictions of all sorts designed for environmental reasons but in actual fact increasing pollution. The differences are also more than socio-economic (*e.g.* income levels or types of households) because variables like levels of activity, car occupancy rates, itineraries and types of vehicles may play a significant role. The increasing variance[62] over time shown in Figure 19 suggests that, ideally, distinct rural and urban model components should be built for Algeria. Regions do not make choices any more than roads do: people make choices.

But formulating distinct models for urban and rural areas raises the problem of the availability of data, notably of the car-km figures necessary to insure the professional credibility of any road safety model (academic publications often meet lower standards on this point, as noted in the discussion of discrete choice models in Part 2). It also raises the following question: should one build, for households and transport companies, distinct models for urban and rural trips, and if so, can one decide this matter except intuitively without complex tests to establish the statistical validity of the difference? Equations for substitute or complementary outcomes like accidents of various severity levels do not constitute independent trials, but the statistical tests used in road safety models have yet to integrate this point: on this question, see Gaudry & Himouri (2012).

Figure 19. Ratio of rural to urban monthly casualties in Algeria, 1970-2006
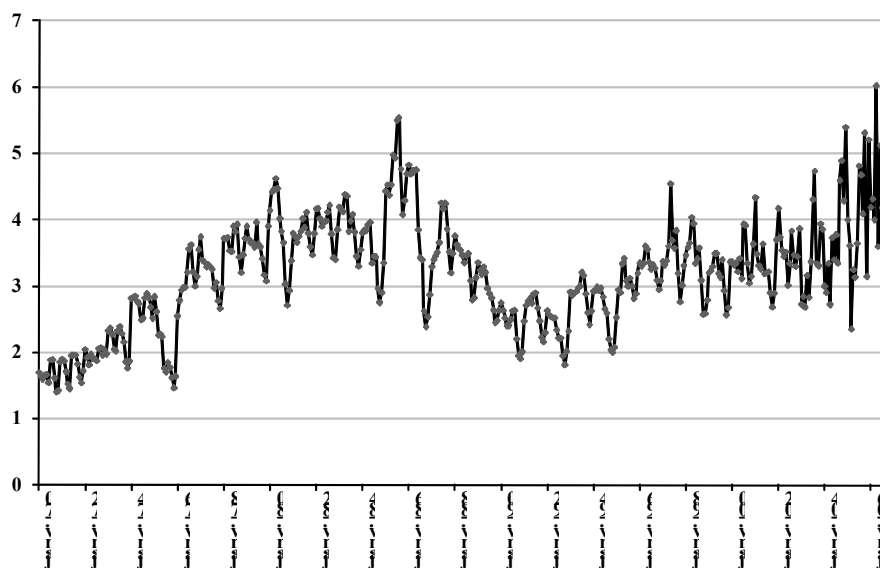
Generally speaking, when population density is used as an explanatory factor of road safety performance, one finds fewer differences between Europeans countries than national averages lead us to expect (Orselli, 2001, 2003). But differences between regional characteristics, including population density, have not yet been studied for our purposes — anywhere — and it is not yet possible to study easily the impact of cultural differences (*e.g.* trust attitude).

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[62] The strong increase in the number of fines handed out to drivers after March 1st 2005 visibly modified the ratio. Between 2005 and 2007, the number of casualties decreased in urban areas by more than 20% but increased slightly in rural ones.

7.1.4. Down from the 1972-73 peak: toward a constant or a minimum?

A. The peak has yet to be explained

However, using one method or another to break down aggregates, or to sum over individual data, by user class may not much help the explanation of the "mystery of 1972-1973". Smeed's simple model loses some effectiveness at high car per capita rates, but researchers using data some 60 years more recent than his sample of 1938 continue to observe an inverse relationship between the rate of equipment[63] and the mortality rate, as shown in Figure 20 where one should note the logarithmic scale on the y-axis, as in Table 3 of Part 1[64].

B. The immediate future: a local minimum or an asymptote?

In any case (with or without a breakdown), the task is not only to make sense of the peak observed in each country — to say nothing about their joint occurrence —, but also to interpret the present trends and to forecast the future. For instance, there is a real question as to whether many current national totals on downward trends since the peak are evolving toward a constant, a sort of asymptotic value of the number of persons killed (and perhaps severely injured), or are approaching a minimum soon to yield a clear turning point. The USA reached a first minimum in 1992 quite distinct from the current decrease of 22% linked to the economic collapse, starting in 2006; Great Britain had a plateau of sorts during the same period (1992-2005) and, in many countries of the EU-27, the year 2007 was the first since 2001 without a decline in the number of persons killed on roads and, in many countries — notably Scandinavian (see Figure 21, after IRTAD, 2008) —, the situation worsened.

Figure 20: Victims killed or injured per car versus number of cars per capita, 29 countries, 1998
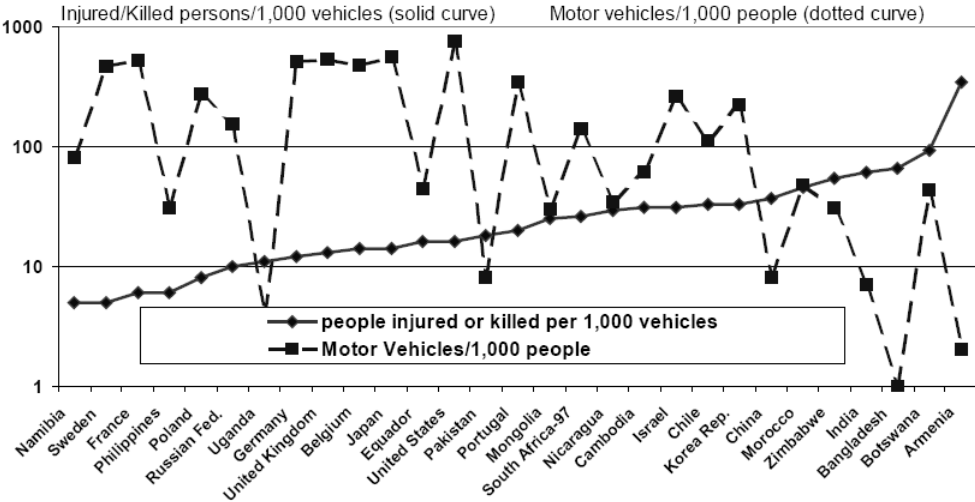
Some 40 years after the peak on 1972-1973, today's fatal accident counts in countries of that vintage may be trending toward a natural and incompressible minimum caused by a random component that implies insensitivity to policy; or they may be following an asymptotic central course with a limit value to be reached when the car occupancy rate reaches 1,00 (*i.e.* 100 in Figure 20), a limit itself dependent on transport policies that deliberately increase traffic congestion. We simply do not know.

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[63] Since the cars per capita increases with the GDP per capita, the mortality rate naturally decreases also, but we cannot conclude that this is a direct explanation.

[64] The source of Figure 20 is Tegnér (2004), based on www.worldbank.org/data/wdi2000/pdfs/tab3_12.pdf.

Figure 21.Recent evolution of road deaths in various countries
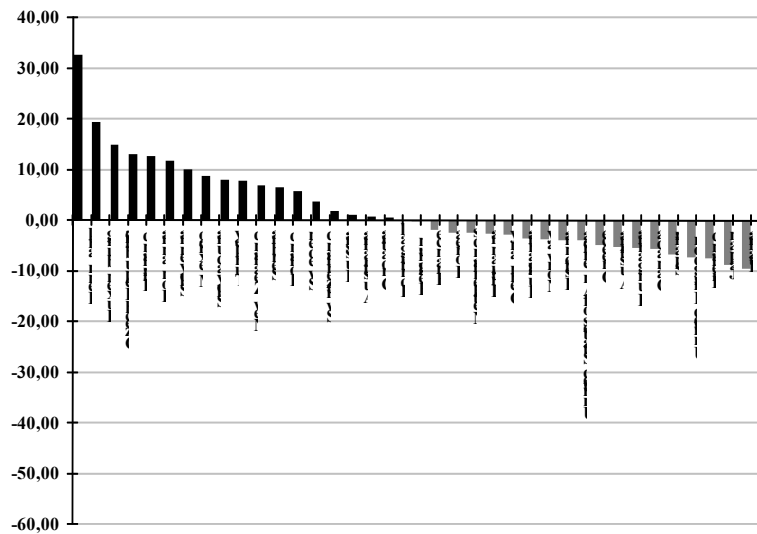
But the slide along the asymptotic curve might not be smooth. Many factors could signal a rise in road deaths: (i) the aging of the population of drivers; (ii) increasing impunity for illegal or dangerous driving, and not only when no-fault insurance systems are set up, as in Quebec, Canada, and Victoria, Australia, jurisdictions; (iii) increasing economic activity; (iv) the refusal to adopt a "pay as you drive" insurance system for consenting adults (insurers and drivers) based on some real-time GPS link allowing for the replacement of an average fixed premium rate by a marginal one (as in Table 14); (v) driving behavior that spends away the safety benefits provided by new automobile technologies or new information because drivers forced into safer vehicles attempt to maintain their desired risk level (or re-establish it).

Below, we formally put the question of what best to expect if the accident determination structure is indeed conducted by the PIMCYÂ factors combined to a random term.

7.2. The bottom up probabilistic road has fewer markers

7.2.1. Demand models have paved the way to aggregation

The explicit re-aggregation of results obtained with models based on individual observations requires, as seen in Section 6 of Part 2, data on the distribution of variables as well as the use of particularly complex elasticity formulas such as those found in manuals (*e.g.* Train, 2003, 2007). The simulations proposed by Bolduc *et al.* (1993, 1994, 2012), remain an exception in that "bottom up" aggregators (from some 8 age groups) work back to population values.

7.2.2. The multiple moments of an explained variable *y*

In addition, other elements found in the practice of discrete models, such as Logit or Probit, differ from those found in aggregate models and differentiate them further: to this day, they only explain the first moment of the choice probabilities and never go beyond. For example, they show no interest in explaining the median probability or its asymmetry.

It has been implicitly assumed in this state-of-the-art survey that regression models explain the first moment of the dependent variable *y* and no attention has been paid to more complex work putting emphasis on the explanation of higher moments of the distribution, such as the second or third. It is possible to characterize driving risk as choices among such moments of

road accident risk, as illustrated (Gaudry, 2006) in an application of seminal work by Allais (1987) demonstrating the relevance of all moments of a random variable to determine utility.

One can easily understand why the Allais approach interests those studying other risks, such as gambling and lotteries where the use of the third moment of return is considered as critical (*e.g.* Pur…eld & Waldron, 1997). But, currently, only models of levels (all with aggregate data in our problem) have ever used a multiple moment approach: we have not found cases of Logit models where, say, the derivatives of the asymmetry (third moment) of the choice probabilities are calculated. So there might be lessons to be learned from finance as well.

Indeed, road risk analyses combine mathematical complexity with an obsession for the first two moments and it is sometimes hard to tell which one plays a greater role: clearly, modelers can do better than the estimation of little expected utility models where the critically important third moment is ignored. In fact, the study of accidents should be a prime field of application for serious portfolio choice theory because driving choices are as frequent, complex and universal as financial choices — if not more.

8. Models and forecasts: toward an incompressible asymptotic limit?

8.1. The relative roles of [P, I, M, C, Y, Â] and of random terms for forecasting

8.1.1. The unavoidable systematic and random parts of models

To better understand the future of modeling and the value of models in forecasting, let us in Table 13 rewrite the framework previously outlined and defined in detail in Table 5 (or in Table 6) by eliminating indexes, stating the vector of systematic factors [**P, I, M, C, Y, Â**] and combining for simplicity the accident frequency and severity dimension as **[A-G]**.

We emphasize again that the vector of systematic factors contains economic activities [**Â**], the "fourth pillar" of road safety analysis, because transport is a derived demand. For each of the equations of the system, there is also a random term which can have more or less complicated properties, as discussed for instance in Equations (9-2) and (9-3) of Part 2 to classify aggregate models based on normally distributed final errors.

Table 13. Simultaneous multiple-level road safety modeling structure

	Dependent		Endogenous explanatory	Exogenous explanatory	Risk component
1	[DR-OCC]	←	$f^{d,o}$ { [CC] ; [A-G]* ;	[P, I, M, C, Y, Â]$^{d, o}$ }	*exposure: kilometers and occupation rate*
2-3	[A-G]	←	f^{a-g} { [DR-OCC]; [CC] ;	[P, I, M, C, Y, Â]$^{a-g}$ }	*accident frequency and severity*
4	[CC]	←	f^{cc} { [DR-OCC]; [A-G]* ;	[P, I, M, C, Y, Â]^{cc} }	*driving behavior (care)*

8.1.2. Is the uncompressible random part of the A-G equations a natural rate?

The rewritten table does not imply that explanatory variables are the sole source of our understanding because the random errors introduced in Part 1, and fundamental to the analysis, should be added to the table. In fact, the many models that explain accident by severity category have found, with both aggregate and count data, that the proportion of randomness tends to increase with the severity category under analysis.

Also, we believe that there always exists in accident occurrence a part that has nothing to do with the transportation network because there exists a point at which further investments in the safety of a network will yield no improvement in road safety whatsoever. Those working in the quantitative assessment of road safety should at some point be able to measure this bottom line beneath which all intervention to improve safety becomes ineffective. When accidents become neither predictable nor controllable, the issue is then whether the remainders are purely random.

One view of this unresponsive component is that it partly corresponds to a natural rate of serious or fatal accidents (and perhaps of material damage ones as well). This vague idea is of something between pure randomness and responsiveness to safety investments: for instance, the built-in "quality" of drivers related to the age-sex structure could well determine a component of such a natural rate. The issue becomes whether all of the [**P, I, M, C, Y, Â**] factors, say for instance cultural attitudes to risk taking, are amenable to modification or not. On this point, what do international committees on road safety say about what can be done? After answering this question, we develop a view that seems more general and realistic than that of a natural rate: we will outline views based on conditional expectations.

8.2. The two-sided Wisdom of the World

International committees on road safety policy have published numerous reports and recommendations. For example, some of the latest recommendations addressed to the European Ministers of Transport (CEMT/OCDE/JTRC/TS1/RD, 2006) dealt with two main issues: key safety variables and national road safety targets, an emerging topic.

8.2.1. The four horsemen of the Apocalypse

The international consensus on road safety seems set on the factors most likely to respond to intervention. All international reports involve the following four, always the same: two components of driving behavior [**CC**], speed and safety belts, and two components of [**C**], excessive alcohol consumption and risk taking among the young.

A recent and most representative example (ITF/OCDE/JTRC, 2008a) is the result of a committee which sat for two years with two representatives of 21 countries and three international organizations. For the first time, three new variables were added to the original four[65]: the quality of the infrastructure and of related emergency medical services, contained in [**I**], and the importance of new vehicle safety technologies affecting [**M**]. The latter technologies are called active/primary (*i.e.,* capable of affecting the probability of accidents) or passive/secondary[66] — typically built into automobiles and capable of affecting the severity of accidents — such a speed limitation devices on heavy trucks.

Similar reports systematically avoid addressing the issue of the "level of the sea" determined in large part by [**Â**] and the number of motorized vehicles in [**M**]: the "sea level" is indirectly dealt with through a study of simple trends which precisely avoid explaining the level itself. These fashionable trends are all linear and negatively sloped, as we now see.

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[65] The members of the committee did not define improvements in infrastructure *e.g.* road resurfacing. They did not raise difficult questions such as risk compensation following the adoption of new safety technologies.
[66] In insurance language, these corresponds to self-insurance expenses that reduce the probability of an accident and to self-protection expenses that reduce the severity of accidents.

8.2.2. Are national studies of safety targets placebo exercises?

The most interesting aspect of the previously mentioned report can be found in the Annex (ITFOCDE/JTRC, 2008b) which deals with the recent hope of reducing the death rate on roads through the establishment of national targets. Strictly speaking, these targets are not forecasts but sorts of extensions of trends[67], amazingly all linear and decreasing except in the case of three of the 40 jurisdictions involved, even when the sample includes a clear maximum or two maxima, as in the case of New Zealand (in 1973 and 1987)[68] and of the United Kingdom (in 1969 and 1972)[69].

None of the 37 jurisdictions involved in the production of a section on their own data make use of turning curves or of polynomial trend estimators provided by Microsoft EXCEL. In addition, nowhere did we see rising national targets! We found a few tentative studies of trend breaks only in research work elsewhere (*e.g.* Antoniou *et al.,* 2008). This means that we get national targets only if the trend is downward: upward trends do not exist. The trend also has to be linear even if this amounts to ignoring the existence of an obvious maximum. Recognition of maxima would require admitting we do not know much about the basic evolution of national road fatalities since 1965, and would surely call for explanations.

Consequently, we wonder if those who appear to believe in national targets, such as Broughton *et al.* (2000), aren't actually only saying that it is useful to superpose to an unexplained trend (also called "numerical context") the effects of proposed regulations that can in principle be separately identified. We have not found statistical demonstrations of beneficial effects of national road safety targets but only discussions of specific national road safety programs designed to improve the overall performance of the transportation network.

Proofs of the effectiveness of the adoption of targets would have to be established jointly with an explanation of the time profile of the evolution of fatalities (and more…) and demonstrate the value added of targets on a background where the Meadow/*Matterhorn*/*Cervin* peak has been made sense of and the shape of the slope and of the valley or plain assessed. A recent perspective on the latter is that of Vision Zero, proposed as a happy end to the story (if not of History…).

8.3. Trends, asymptotes and Vision Zero

What is Vision Zero? An objective, because knowing where one is going should be useful in getting there. But where is there and is it nowhere? Ideally, we all want roads, cars and drivers to be safe so as to bring the number of road casualties and accidents causing serious injuries down to zero. This is an ambitious program with wide repercussions, orienting planners toward the notion that the traditional balancing of mobility and safety on roads has become morally unacceptable (Tingvall, 1997, 1998). Just another slogan?

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[67] The only jurisdiction that has produced actual short-term (1 to 7 year) forecasts is the SAAQ (*Société de l'assurance automobile du Québec*) by using a structural model ― not by extending trends. For about 10 years after 1993, the SAAQ developed the DRAG-2 and DRAG-3 models for monthly forecasting purposes (Fournier & Simard, 1997, 1999, 2000). As a governmental body with a monopoly on insurance for accidents causing bodily injury, the SAAQ is compelled to publicly document its official model use, a task performed in this case with over 1000 pages of public documentation (Gaudry *et al*., 1993-1995).
[68] Surprisingly, Stipdonk *et al.* (2005) use a monotonic curve to describe the New Zealand "trend" with a sample that covers the years 1980 to 2005 and contains multiple maxima and a peak.
[69] Sweden, which has two maximum years with comparable numbers of fatalities, is not among the 34 jurisdictions whose national targets were part of the preliminary version of the report we examined.

Vision Zero ignores entirely new automated transport systems like *podcars* (PRT) that, while respecting present freedom of movement, would substitute safe equipment and computer algorithms to unsafe vehicles and high-risk drivers. While we wait for major technological breakthroughs and their market implementation, Vision Zero concentrates on what seems available like planned active safety[70] technologies being included in cars built today. In fact, the plan of Sweden's Ministry of Industry, Employment and Communications (MIEC, 1999), approved by Government in 1998, included 11 means, some more concrete than others, presented as a *smorsgasbord* that includes the "Forgiving Highway"[71] in a long and heterogeneous list[72].

8.3.1. A Land of Cockaigne

Unfortunately, in order to create such a paradise on earth, every part of the transportation system would have to work perfectly, at the highest level of efficiency and at immense cost. Zero Vision does not take costs into consideration; but costs are, of course, at the very center of automobile design, of road design and construction, of quality control on roads and on the whole transport network. For example, railway and subway car designs are often approved on the basis of a frequency-severity trade-off assessed by simulating real conditions. Thus, implicitly, the outcome of the trade-off is decided by established standards and by the cost of implementing them.

8.3.2. How far are we from Vision Zero?

What were the effects of the adoption of Vision Zero in Sweden? The official brochure of the Swedish Road Administration (SRA, 2006) simply states that "since the adoption of Zero Vision [in 1998], the death toll on Swedish roads has declined". On the other hand, international experts (Breen *et al.,* 2007) argue the opposite: that the death toll has increased since the adoption of the policy. Let us look at some hard facts in Figures 22 and 23.

The series presented in both graphs indicate that the number of deaths since 1998 (official year of the adoption of the Zero Vision policy) has remained stable. The cumulative variation of 12 in the number of persons killed on roads between 1997 and 2007 (included)[73] suggests that a break in the downward trend occurred before 1998. Moreover, the death toll increased by 8% between 2005 and 2007 and then fell to 397 in 2008 and 358 in 2009. Was the 2007 value a final spurt (472 dead and 4 000 injured) before the financial recession and crisis of 2008? The data shown in Figure 22 and the slowing down of improvements shown in Figure

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[70] This comprises the use of sensors keeping drivers awake or correcting the trajectory of a car on a collision course or automatically putting the brakes on (keeping the car stable) to prevent an accident sensed by the car's front and rear sensors. Some of these devices are both passive and active. The *Limitator* or LAVIA (*Limitateur s'Adaptant à la Vitesse Autorisée)* can both tell the driver what the speed limit is on the current road and actively act upon the car's speed (Ehrlich, 2006).

[71] The Forgiving Highway is built to redress driving mistakes. For example, France has cut down trees along roads (which accounted for 10% of the casualties in the early 2000's) in this perspective.

[72] According to the report written by experts Breen *et. al.* (2007), "The 11 points proposed in the plan included: 1. Identifying and treating the most hazardous road sections; 2. Making traffic safer in towns, by rebuilding streets according to the design principles of *Vision Zero;* 3. A stronger emphasis on the responsibility of road users; 4. Safer cycling, especially through means of promoting helmet wearing; 5. Safety audit of transport services purchased by the public sector; 6. A law requiring the use of winter tires on slippery roads in winter; 7. Exploiting Swedish technology to make motor vehicles safer; 8. Codifying the responsibility for safety of those who design the road transport system; 9. Reassessing penalties for traffic law violations; 10. Clarifying the role of voluntary associations and organizations working for road safety; 11. Experimenting with new systems for financing new roads."

[73] In particular, the number of deaths of the motorized two-wheel category has increased from 50 to 80 per year from 1997 to 2004.

23 point to a state of stagnation. It would appear that Sweden's Vision Zero objective has not progressed much since its adoption. Will the same thing happen elsewhere?

Figure 22. Annual number of road deaths in Sweden over 58 years (1950-2007)
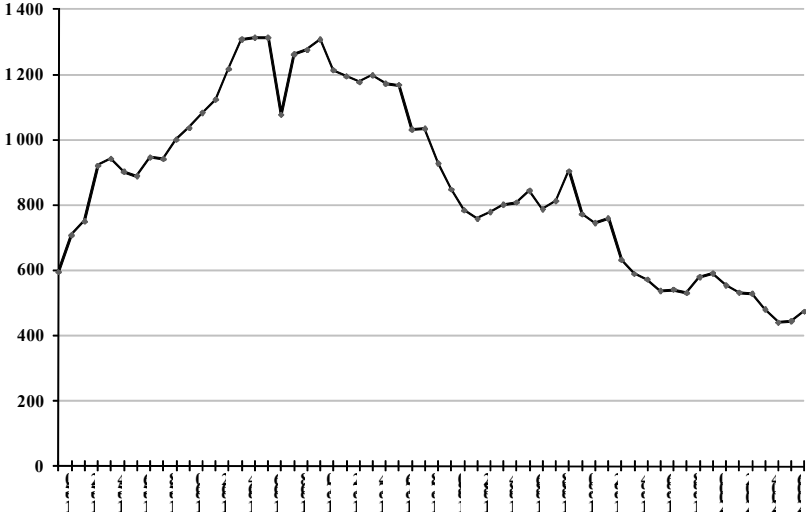
Figure 23. Year-to-year change in road deaths in Sweden over 57 years (1951-2007)
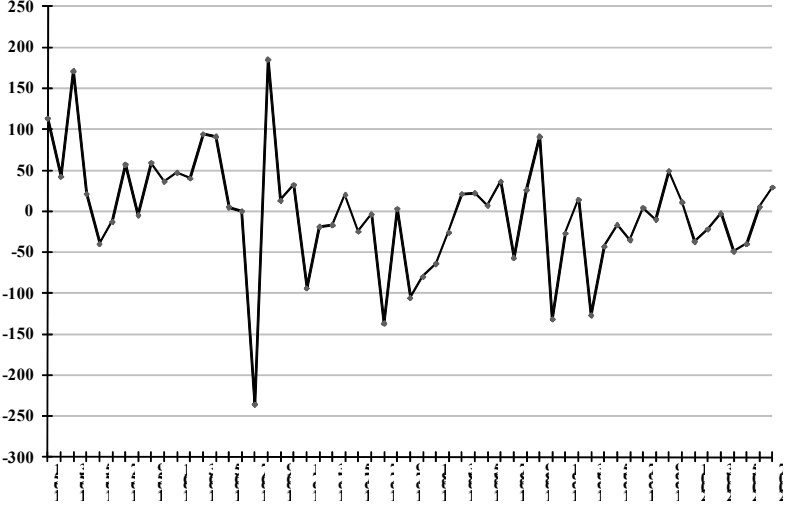
The question is then whether there is really an end-point, or limit, to the evolution of all national safety aggregate indicators, and notably of fatalities. To answer it, one needs to place Vision Zero in a wider modeling context by taking into account both random effects and the more systematic ones included in PIMCYÂ. We will retain some link to other statistical fields where the use of a "natural rate" is common practice in countries where these rates are considered as incompressible, at least for unemployment; but we will try to make use of what models teach by pointing to hard cores in many of the factors.

8.3.3. Systematic effects lurking above any fundamental randomness or natural rate
At first glance, a natural rate of road "insecurity" would correspond to the random side of the model: by definition, it is not compressible and resists regulation. It has been mentioned above that the role of randomness is more important in fatal accidents than in accidents with injuries: a natural rate would be the level implied by severity-specific randomness. But what then happens to the systematic "regression component"? How do values progressively reach the random level? The regression component has to be a part of a reasonable answer.

To be practical, we ask simply if it is feasible to reduce by a factor of 10 the number of deaths on roads in, say, France, from the peak just below 20 000 of 1972. A toll of 2 000 would do and (adjusted for population) match the 1 400 level caused by horse-drawn carriages before the war of 1870, as shown in Figure 2 of Part 1. A toll of 2 000 implies a 60% reduction from the level of 2005 and a 50% reduction from the value of 4 000 experienced in 2010 and 2011. What do the systematic model components tell us about the possibility?

9. Conditional expectation of national tolls: 10% of the 1972 peak for France and others?

The PIMCYÂ variables listed in Table 13 "displace the random term": they constitute the "regression component" already lurking in the Bortkiewicz analysis of horses' kicks, as discussed in Part 1, and made no less important by the advent of motor-powered vehicles. Consequently, a discussion of road safety performance perspectives within the framework of multivariate modeling naturally requires that we first look at the first moment of national performance indicators and more precisely, at their *conditional expected value*:

(17)   { Expected value of [road safety indicator] }←{ f (PIMCYÂ; randomness term) }

This simple formulation is easily understood in an aggregate model, including those where the dependent variable is subjected to Box-Cox transformations. It also has a precise analytical meaning in Logit-type models (12)-(13) where it is defined by a function of the denominator of the share or probability of potential outcomes forming the relevant support of an expected maximum insecurity (EMI) measure[74]. In all models, both aggregate and discrete, PIMCYÂ explanatory variables must be given values (or even a distribution of values) for the expected performance to be calculated. Instead of discussing hard core limits for each category of variable, we approach the matter by theme.

Public policy influences expected road safety performance but so does the driver's compensatory behavior and, even more so, the demand for transportation derived from economic activity, and the prices involved. As each of these three dimensions intersects with many of the PIMCYÂ sets of variables, we structure our discussion accordingly. This approach raises the main issues which all forecasting models have to face and stresses the relative importance of the factors, whether one is interested in the possibility of dividing yearly fatalities by a factor of 10 or in finding a solution to growing global road death toll.

9.1. Expected road safety performance and the political market

The political market has multiple effects, notably: on **[P]** with taxes on vehicles and on gas, fines and road tolls, the imposition of compulsory insurance and the setting of premium price structures (sometimes capped and twisted for political reasons); on **[I]** with road standards, speed limits, Highway Codes and traffic flow management; on **[M]** with technical standards for vehicles and their use; on **[C]** with access to driving permits, licenses and other access requirements (*e.g.*, medical conditions; Blood Alcohol Concentration), and on **[Y]** by driver education and the handling of serial infractors.

But instead of considering all these wide-reaching means of intervention, the forecasting of regulation is often limited to the four Horsemen of the Apocalypse. The wider problem is

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[74] Gaudry & Vernier (2000) applied this notion, analogous to the Expected Maximum Utility (EMU) commonly found in Logit mode choice models, to the frequency and the severity of road accidents. The denominator is subjected to a Box-cox transformation, a special testable case of which is the *Logsum*.

indeed one of forecasting the political market on many more points: for instance, restrictions on engine horsepower or speed, the imposition of day time running headlights and control of motorcyclists[75] are primarily political issues, and have a limited technical dimension, in contrast with say noise and emission standards. If this is the case, who is at the wheel?

The application of political economy theory to road safety is not frequent. A promising[76] testable hypothesis suggested by many researchers to explain the evolution of safety regulation, speed limits, technical standards[77], insurance systems and fines, is that the median voter is in fact at the wheel. Let us examine the political scene that seems to have such an influence on road safety policy and regulation.

What can be expected from government policy in support of the objective of a reduction by a factor of 10 of the peak number of accidents? How flexible are government interventions in democratic countries? We discuss regulations in order of increasing feasibility.

9.1.1. Constitutional constraints as immovable objects

Democratic societies impose some immutable limits to regulation: those of equal rights, for instance. Building a road where one could guarantee to halve the casualty rate by allowing only men and women drivers between the ages of 35 to 45 (see Figure 7.A in Part 1) is unthinkable in a democratic society. Even if such a road were profitable and self-financed, democratic governments would have to amend their constitutions to allow it.

Now, would the median voter agree to this idea? More often than not, amending a constitution requires the agreement of a majority of voters and sometimes even of two thirds of them. In addition, political moves would make the process of constitutional amendment very slow and all but surely kill such a road project. Equal treatment can therefore stand in the way of more expensive, but safer roads: relatively safe drivers have no choice but to share the road with all of those who are allowed on it by the unforgiving tyranny of the median voter.

9.1.2. Regulations subjected to short term modification

In democratic societies, there are some limits to the flexibility of allowable regulations and to the ease with which they can be modified. Consider for example, the criteria of admissibility to a driver's license, a factor that greatly influences the average safety of the stock of drivers: obtaining a driver's license is not a constitutional right but is regulated by political decisions through the setting of access criteria (age, medical condition, *etc*.).

To use again an example based on average age-sex differences, could a government use an "age-sex envelope approach" and put strong constraints on the licensing of young men and old women to favor young women and older men (see Figure 7.A)? It is difficult to imagine a politician bolder on such a point than what the median voter may think is acceptable. For

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[75] For instance, passing between cars is forbidden to motorcycles in Canada (the country of snow), authorized in California (Hell's Angels' territory) and tolerated in France.

[76] Laurent Carnis, of *Institut Français des Sciences et Technologies des Transports, de l'Aménagement et des Réseaux* (IFSTTAR), has suggested that the evolution of regulation since 1970 be studied with the median voter model (in the context of the rise and decline of the baby boom) as the main hypothesis.

[77] Generally speaking, transportation experts do not consider compulsory vehicle inspection and maintenance regulations to be anything other than local job creation programs. Fosser (1992) has shown with refined data, that there is no link between accidents and the frequency of inspections. With aggregate data, Loeb (1988) has found favorable effects in some U.S. states. Tegnér (2000), using monthly time series for Stockholm, found that an increased proportion of vehicles with faulty brakes was associated with a rise in bodily injury accidents.

instance, should there be opposition by motorcyclists to day time running headlights, some politicians will trade the saving of unidentified lives (by an effective and cheap policy) against identifiable vocal votes: sometimes, no profit is too small.

9.1.3. Unstable regulations: speed limits and automotive fuel taxes

The behavior of drivers **[CC]** is a critical safety factor, but speed limits are accepted by slim majorities of voters, as demonstrated in the USA where the 51 States change them frequently. The same holds for automotive fuel excise taxes, like the new regional levy[78] introduced in France in 2007: it can be predicted to change often (within the central government imposed limits) because the median voter changes with each regional election campaign: Grabovski & Morissey (2006) have counted 253 fuel tax changes in the U.S. from 1982 to 2000.

In countries with decentralized authorities, speed limits and taxes on fuel are then unstable and can be better explained by yo-yo theory than by theories on spinning a top or on long-term national "good intentions" or targets. In other words, they cannot be relied on to consistently help reach higher safety targets.

In addition, should the foreigners' rent on oil rise, some local and central governments will choose to reduce the domestic tax on fuel rather than raise it and increase revenue at the expense of countries that are not all our friends. Current chances are that, the scarcer and dearer fuel becomes, the more governments will try to keep its price at the pump low. Governments easily forget that fuel taxes are specific user charges (Prest, 1963) and that the highway network cost recovery rate is often insufficient, especially for heavy goods vehicles, a situation that could and should be redressed[79]. Consequently, governments will refuse to transfer the oil rent from foreigners to national budgets because median voters prefer their cars to national energy autonomy, the capture of oil rents and better terms of trade.

9.1.4. Instant and dubious regulation: taxing energy-consuming vehicles

Instant regulations may well be the fastest and easiest government measure to implement. For instance, Canada, Spain, France and other countries have in the last 5 years or so imposed a tax on the sale of "high consumption" vehicles. This decision, which might still have some consequences on road safety that cannot yet be discounted, seems to have been taken pretty much without public knowledge or debate, almost furtively. Given the fact that many other countries are planning to adopt similar measures, let us examine its effect.

Citizens buy heavier vehicles, supposedly safer that than the average ones, it could often be because they perceive the risk of driving to be excessive in lighter vehicles or simply because they want to move large families. There are indications that this safety motivation might decrease if some recent U.S. findings (IIHS, 2011a) pointing out that the aggressiveness of minivans and sports utility vehicles relative to that of cars has decreased considerably for recent vintages (2008-2009 model years) due to greater homogeneity in safety design: the "externality" argument is reduced even if some clear advantages of weight linger on[80].

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[78] In France, the former name of the fuel tax, TIPP (*Taxe Intérieure sur les Produits Pétroliers*), was changed in 2011 to TICPE (*Taxe Intérieure de Consommation sur les Produits Énergétiques*) but the regional ad-on were maintained: in 2011, 17 regions used the maximum supplement of 2,5 eurocents per liter of diesel or gasoline allowed by the central government, 2 used none and 3 applied a compromise rate.

[79] There exist cost recovery rate summaries by user class for North America (Gaudry, 2005) and France (Gaudry & Paul-Dubois-Taine, 2009).

[80] For instance, heavier hybrids seem to protect their passengers better but pedestrians less well (IIHS, 2011b).

Concerning then the taxation of larger vehicles on the basis of their production of greenhouse gases, France and Spain — where heavy vehicles happen to be foreign — pretend to tax the sale of these vehicles for environmental reasons. The problem with this argument is that greenhouse gas (and pollution) emissions are proportional to energy consumption: to reduce GHG emission levels, honest-talking governments should logically only tax fuel.

9.1.5. Road safety and the median voter

To try to model the link between the behavior of the median voter and the establishment of safety laws presents problems, not the least of which is the asymmetry between the law (based on the median voter) and the risk of accidents (often based on marginal or extreme drivers). The median driver is not the one who determines the safe distance between cars or any acceptance gap for that matter: it is the driver who is willing to take the greatest risk, irrespective of the law. As a result, it can be said that the marginal or extreme driver is the target of policies defined by the median driver, which is hard to model.

When speed limits are changed, the asymmetry of the distribution of individual speeds changes more that the mean or the median of the distribution: what will then be decided if the median wags both the asymmetry of the distribution and its mean simultaneously? It is hardly logically possible to change the asymmetry of the distribution without affecting the median (and the mean and the variance): this presents non trivial logical challenges to the maximization of utility. Mean preserving spread models then appear as easy (one can vary the standard error without affecting the mean) but singularly inadequate and out of touch.

The political market is also a challenge to road safety modelers because government regulations are unstable and can have ambiguous effects. For instance, the installation of lighting on relatively low-traffic road sections (including highways) is generally thought to lower mortality and morbidity rates, at least at low traffic densities[81]. This is explained by the fact that speed limits keep drivers from switching back to the risk level that they would have chosen in darkness. If this is true, it is the combination of lighting and speed limits that saves lives, not the lighting by itself. How can one model the way the political market will decide where and when the lights are kept on?

What can be expected of the evolution of regulations subjected to the vagaries of median voter moods? It would appear that the latter's demand for risk seems stronger than any reasonable value the Vision Zero objective can ever expect to set, let alone reach. This is what the author Albert Camus called "the bloody mathematics of our condition"[82].

9.1.6. The expected death rate is conditional on policy choices

Within our hypothetical medium-term objective of reducing by a factor of 10 the number of deaths on roads, what can generally be said about the influence of government policy on road safety management? The famous Duclos had a lot to say on the subject in 1759 (p.24):

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[81] Some experiments are currently in progress on some highways of the Paris region where there are some reasons to think that this might not hold at high flow rates, as was apparently discovered when the theft of electrical wires turned out the lights on some highway sections.

[82] From: The Outsider (*L'Étranger,* 1942) by Albert Camus who coined this expression and, ironically, died in a car accident.

"[…] Government, badly served, gets more and more into debt & becomes incapable of paying-up unless it changes. Chaos follows: a necessary expense is postponed in favor of useless but anticipatory ones, because debts and favors abolish all barriers.

That was the case of the "Ponts et Chaussées" in France in 1726, when, calling them hard times, M. Dubois sought to reduce influence peddling and other abuses of power".

Now that the demographic *baby bust* wave is passing, who is the new median voter? On the one hand, higher standards of living and education appear to increase the demand for safety everywhere at a rate higher than the increase in average income. On the other hand, higher living standards are often accompanied by increasing laxity in the education of the young and by an overall decrease in holding individuals responsible for their acts. Thus, at best, we can hope for a weak trend toward weak regulation of very dangerous drivers, inasmuch as safety remains a superior good for all, including the median voter who seeks protection from the asymmetric tail of the distribution.

9.2. The complexities of individual risk compensation

This notion of compensation means that, when regulation standards or constraints are imposed, drivers automatically produce compensatory behavior designed to, partially at least, reestablish their desired level of risk. Thus, in the short-term, compensation is expressed by driving behavior in **[CC]** but, in the long-term, it is probably strongly expressed by the safety equipment and devices choices in **[M]**, and even in the demand for exposure **[DR]**.

Compensation usually involves a distinction between reactions to technological change and reactions to price changes. The notion of strict compensation, *i.e.* of compensation exactly equal to the gain, was rejected by Smeed (1949)[83], reformulated by Peltzman (1975), an American economist, and popularized by Wilde (1976, 1982), a Canadian psychologist, under the term "risk homeostasis". The notion evokes a trade-off among first moments of random variables but, in the absence of a strict definition of risk (that would presumably involve higher moments, and notably the third) and of a distinction between risk and uncertainty (used for instance by Gaudry & Vernier (2000), inspired by Knight (1921), remains intuitive.

9.2.1. Compensation following technological changes

Economists would say that technical innovation (in cars and safety devices) cause ― as do variations in price ― a restructuring of the purchased basket (containing substitutes and complements) and a change in the size of the basket (just like an income effect). But how will drivers react to compulsory new safety devices in cars or to the implementation of new safety standards? How much are they willing to accept? And how will they spend their newly acquired higher (and sometimes imposed)[84] standard of living? Will they seek to reestablish the former level of risk: will the additional safety imposed upon them result in a net gain?

The notion of compensation is both hard to define and difficult to verify. It implies notably that a government forcing drivers to buy safer vehicles, or vehicles in better conditions, will have an impact on the speed at which they drive **[CC]**. We are not talking here about the drivers' ability to understand the new regulation but are concerned with drivers' reactions to regulation such as compulsory seat belts or shoulder straps, helmets or safer vehicles.

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[83] «I see no reason why this regressive tendency should always result in exactly the same number of accidents as would have occurred in the absence of active measures for accident reduction.»

[84] During a conversation with one of the authors, Reuven Brenner of McGill University noted that compulsory safety standards lower the cost for all and that everyone gains. The issue is then how this unexpected or imposed gain will be spent.

9.2.2. The seeming beginning of the compensation debate

The improvement of the safety of vehicles is not a recent[85]. Seat belts were added to the Renault Dauphine in 1956 — it became the most sold car in France in 1961 — and recent models are now equipped with dynamic stability systems. Safety improvements have a long history highlighted by a few landmarks such as retractable bumpers capable of resisting small collisions (varying from 5 to 8 km/hr) and safer windshields. In fact, if one cumulated all of the safety gains each technological modification was supposed to produce over the last 50 years, the result would imply a negative number of deaths on roads to-day.

The underlying static but typical forecast of potential gains obviously does not take compensation into account (*e.g*., Joksch & Wuerdemann, 1972, 1973). It works on "fixed coefficients". Look at what is being discussed these days in Europe where it is said: that if "the just before collision" speed was reduced by 15 km/h, the number of deaths would be halved (Tingvall, 2008); that electronic stability systems would reduce the death rate by 17%; that systems designed to bring stray cars back to the centre of lanes would reduce the death rate by 15% and that speed alarms would reduce deaths by 15% (VTT, 2008). The point of forecasting is not to add all these "fixed coefficient" percentages but to find out if the drivers will driver faster, thus taking more risks, if their vehicles are more "intelligent" and safer. In an economic system of supply and demand, a price change generally causes consumers to substitute one good for another, but the substitution is never complete.

Unfortunately, all the gains in safety implemented since 1955 have not produced their expected result. Why is this so? Everybody knows that consumers demand safety equipment and pay for it freely (*e.g*. Winston & Mannering, 1984) even when imposed by regulation. The problem we need to address is the following: how are gains in the potential safety of vehicles spent? Is new windfall "income" applied to reestablish previous levels of risk? Since measuring compensation directly with real speed changes is difficult, modelers adopt an indirect approach. They study behavior (*e.g*. Sobel & Nesbit, 2007) or the changes in the frequency or severity of accidents that come with a given specific safety device or other (Winston *et al*., 2006); or they look at vehicle registration dates and compare "before and after" safety improvements (Broughton *et al.,* 2000). Modelers also studied the frequency of rear end collisions after the installation of cameras at traffic lights (Obeng & Burkey, 2008).

9.2.3. Conditional severity of accidents and the year of first registration of vehicles

How are we to demonstrate the presence of net safety gains after the installation of safety systems in vehicles? The analysis proposed by Broughton *et al*., (2000), in Annex A of their study, seems both intuitively plausible and promising. Their study is based on the following observation: in tallies of accidents that occurred in Great Britain over the years (1981-1982; 1988-1989; 1995-1996), the proportions of both drivers killed P_1 and drivers killed or seriously injured P_2 over all drivers killed and injured in a given year tend to increase with the age of the vehicle. Moreover, this trend shifts downwards the closer one gets to more recent accidents (in this case 1996). Does the influence of safer vehicles appear slowly but surely?

The linear Logit explanation provided by the authors for the proportion of killed P_1 and that of killed or seriously injured P_2 (i) assumes that the age of the vehicle is not a factor that influences the probability of death or injury (no compensation); (ii) explains P_1 and P_2 by

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[85] The first safety-related regulation may have come in 1956 when the U.S. government ordered car manufacturers to install locks than prevented drivers from being ejected in an accident.

taking into account the age of the vehicle and the year the accident occurred, in addition to the type of road (urban or rural) and the age and sex of the drivers.

Unfortunately, it also fails to take into account the 69% increase in traffic[86] that took place between 1980 and 1998 on already congested roads. We will show later, for Norway, that the decrease in mortality and severe morbidity rates (and the reverse increase in light morbidity) may be simply explained by heavier traffic, or what is called the "benefits of density", which in England would be properly be called "congestion" given the fact that the country has the most congested roads of Europe. The observed trends and shifts might just reflect lifesaving congestion and gridlock which prevents drivers from reaching their desired risk level.

9.2.4. Reacting to price and fines

Where does that lead us? All regulations are not created equal: some do not trigger compensatory reactions in drivers. Generally speaking, fines and varied financial penalties affect behavior in ways that do not cause the driver to compensate to recover the same level of risk as before the traffic violation. Since drivers are sensitive to the amount of fines, increased fines or changes in the insurance system produces reactions (Rea, 1987) generally easier to detect than reactions to technical changes (Gaudry, 1992; Krupp, 2005). The price of fuel and the cost of insurance premiums have a large impact on speed and risk taking. A good example of this is the experiment undertaken by Great Britain's Norwich Union insurance company which, starting in 2006, tested a real time (GPS-based) variable marginal cost-type insurance policy — as opposed to a fixed premium policy: it was reported (Crampton, 2007) to have produced[87] a strong reduction in the number of accidents, particularly those involving young drivers at night and on weekends.

9.2.5. The expected number of accidents is conditional upon compensatory behavior

Overall, researchers expect partial compensation for all technological safety gains, no compensation for fines and high levels of compensation in reaction to insurance systems based on marginal cost pricing. The latter has been strongly advocated by experts since Vickrey (1968). Table 14 shows that the rating tried by Norwich Union closely resembles such a system: finally, a measure with large expected gains!

Table 1. Cost of home bound leg of trip for drivers aged 24 to 65 (Norwich Union)

	2,3 miles on single lane road	1,2 miles on highway	2,6 miles on single lane road	2,3 milles on highway	**TOTAL 10,7 miles**
Off-peak	9.2 pence	1.2 pence	10.4 pence	16.1 pence	**36.9 pence**
Peak: 23h00 to 6h00	13.8 pence	1.8 pence	15.6 pence	27.6 pence	**58.8 pence**

We have not documented the large literature on insurance *régimes*, which includes major issues such as compulsory insurance and pure no-fault (abolishing the tort system), or the growing refusal of legal discrimination on the basis of sex and age. Changes in insurance liability frameworks predominantly cause parallel shifts in safety indicators that affect the level of any asymptotic limit. But shifts are precisely what is expected of possible measures such as per kilometer insurance pricing, on a background tide level driven by the economy.

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[86] Gas consumption increased by 16% and diesel fuel consumption by 120% over this period.
[87] Contact made with the company to understand why the experiment was abandoned were unsuccessful. In an imperfectly competitive industry where mark-up determined profits exist, safety measures that decrease the volume of business might be very difficult to implement.

9.3. The economy, transport and road accidents in the short-term

That the demand for the transportation of people and goods is derived from economic activity is a fact we cannot ignore: we named it the "fourth pillar" in Part 2. In order to determine the specific demand made on roads and the loading intensity of vehicles on the network, all dimensions of which in **[DR-OCC]** are of capital importance in explaining **[A-G]**. This is seen symbolically in Table 13 and in reality throughout the evolution of aggregate modeling: the overall demand for transportation and the modal choices resulting from economic activity are unavoidable.

No matter the preferred model structure, it is necessary to explain the number of freight and passenger vehicles in use **[DR]** and the intensity of this usage **[OCC]**. It is clear that limiting the analysis to government regulation and to drivers' compensatory behavior will not suffice to forecast road safety performance.

Even if accidents just happen and if not all ships sink, we still need to know how many vehicles there will be (the level of activity, or tide) and their loadings. A model that does not correctly take exposure **[DR-OCC]**, be it the explained or explanatory, into consideration lacks an engine, as pointed out in the discussion of some discrete accident frequency models in Part 2. Let us first look at **[OCC]** and **[DR]** through the lens of a short-term model. The medium-term and the inevitable and critical role of economic growth will be discussed later.

9.3.1. The car occupancy rate

How should one interpret Smeed's model? Let us first restate it as a function of the rate of occupancy of vehicles. This amounts to replacing the explanatory variable by its inverse in equation S-1 of Table 3. The result of this substitution, seen in equation C of Table 15, shows after some trivial manipulation the number of casualties to be proportional to the size of the fleet and infra-proportional to the occupancy rate (or load factor) of the vehicles.

Table 15. Reinterpretation of Smeed's model and addition of speed and density effects

Smeed's (1949) equation S-1 rewritten in terms of OCC, the occupancy rate of vehicles			
S-1	(Killed/Vehicle) =	$k_a \bullet$ (Vehicle/Population) $^{-2/3}$	**A**
	(Killed) =	$k_a \bullet$ (Vehicle) $\bullet$ (OCC $^{-1}$) $^{-2/3}$	**B**
	(Killed) =	$k_a \bullet$ (Vehicle) $\bullet$ (OCC) $^{2/3}$	**C**
Nilsson's (2000, 2004, 2005) equation re-estimated by Elvik *et al.* (2004)			
	(Killed) =	$k_v \bullet$ (Speed) ^{4,5}	**D**
Combining equations C and D and adding an hypothetical Speed-Density conjecture			
	(Killed) =	$k_{av} \bullet$ (Vehicle-km) $\bullet$ (Speed) $^{4,5} \bullet$ (OCC) $^{2/3}$	**E**
	(Killed) =	$k_{av} \bullet$ (Vehicle-km) $\bullet$ (Speed) $^{\alpha} \bullet$ (Density) $^{\beta} \bullet$ (OCC) $^{\gamma}$	**F**

Given that this new formulation is the product of various variables explaining the number of casualties, the elasticity of this number with respect to fleet size is calculated by summing the elasticities of each term, in this case equal to the coefficients: [1 + (-2/3) = 1/3]. In Smeed's model, an increase of the fleet would thus imply a proportional effect linked to vehicles, that can be interpreted as a frequency-exposure effect, and an infra-proportional effect linked to the occupancy rate interpretable as a conditional severity effect. Assuming that the mileage per vehicle is constant, the line C explanation in Table 15 allows a modeler to artificially

associate one-to-one the frequency level to the size of the fleet and the morbidity rate to the occupancy rate **[OCC]**; and similarly for other bodily injury classes of victims.

What are then the conditions under which an increase in the number of vehicles on the roads and a corresponding identical percentage decrease in the occupancy rate imply a less than proportional variation of the number of deaths, *i.e.* a "decreasing marginal rate"? In other words, the problem is to understand how the transformation of passengers into drivers reduces the number of victims by vehicle: two people driving one kilometer in the same car would produce a higher death rate than two people driving the same distance in two separate cars. Is this a questionable dream?

A first interpretation of this stunning result of increased fleet size [1 + (-2/3) = 1/3] amounts to saying that, given constant speed, the lower car occupancy rate reduces the morbidity rate of accidents that might still occur as often as before per kilometer driven because higher occupancy of vehicles increases the chance of bodily injuries at a constant speed. Less strictly stated, the interpretation is of a morbidity rate decrease that offsets the vehicle-km exposure effect to yield total casualties increasing less than proportionately to increased fleet size. In all cases (whether the frequency elasticity of fatal accidents per vehicle-km remains constant or presumably falls), it attributes a major offsetting role to the load factor, a variable which has not been much studied specifically by modelers.

9.3.2. The unobserved speed

Another way of interpreting this surprising result is to bring the speed of vehicles into the analysis; and we shall see that this could even result in decreases in fatalities. To do so, let us look at Table 15. It presents a simplified version of the equation Nilsson formulated in various Swedish reports that predate the better-known 2000 version (also found in his dissertation of 2004). His original power values presented in Figure 24 were further refined by Elvik *et al.* (2004).

Figure 24. Relation between speed and number of road casualties (Nilsson, 2000, 2004, 2005)
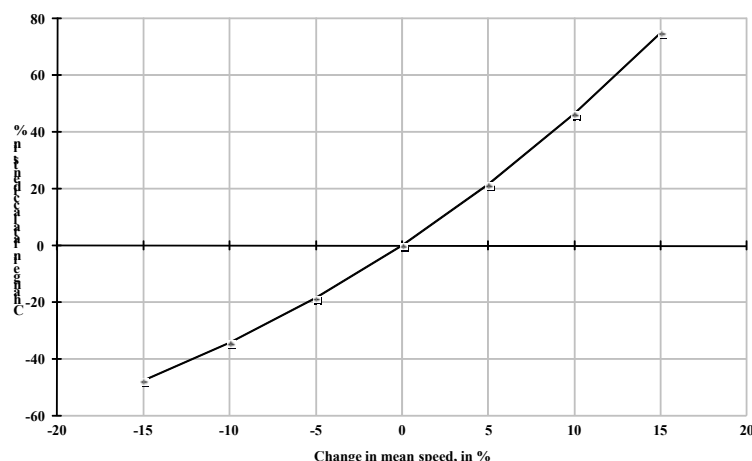
This second interpretation is plausible because Nilsson's "Power Model" does not distinguish between the effects of speed on the frequency and on the severity of accidents. It thus simply consists in (i) attributing the desired effect to a change in speed; (ii) simultaneously implicitly denying that the joint probability of death is lower if two individuals drive the same distance in separate cars than if they drove together.

In fact, the issue becomes whether the gain in safety attributable to increased fleet size results not only from lower frequency and severity rates at constant speeds but also from lower frequency and severity rates due to speed, both more than offsetting increased exposure effects. If, as many believe, equation D in Table 15 shows the net effect of speed, a slight reduction in speed[88] is sufficient to produce a major reduction in the number of deaths even if the conditional frequency and severity rates associated with the occupancy rate remain unchanged.

So then, why would people slow down when there are more vehicles on the road? It is a fact that in OECD countries where fatalities peaked in 1972-1973 the share of public investment expenditure on highways started falling in 1967, long before the fleet size shift (increase) that started in 1970. The latter trend break led OPEC to raise the price of oil in October 1973. Slight increases in traffic density may well have caused decreased "free flow" speeds over and above their effect on congestion levels proper. The high speed exponent (Nilsson's original number or the higher value of 4,5 recommended by Elvik *et al.*, 2004) is sufficient to explain that safety gains (benefits of density) can be obtained from small increases in traffic density, irrespective of other factors.

9.3.3. Using density as a proxy for unobserved speed

Fridstrøm (1999, section 6.7.1), for one, designed a model that distinguishes the effect of traffic volume from the effect of traffic density and found an elasticity of bodily injury accidents with respect to traffic volume of 0,91 and with respect to traffic density of – 0,42. This is a "meso-economic" density, by county, for basically uncongested roads: we know that, at the road link level, an increase in density will ultimately lower the sum of the two elasticities because the microeconomic frequency-delay or cost-delay curve relationship on road links is of a reversed-U shape[89] illustrated in Figure 25 (Gaudry, 2000, Figure 1.3), as demonstrated by Cohen (1980) in his Masters' thesis and used (in strict quadratic garb) for intersections of (2x2) = 4-lane urban roads (Persaud & Lyon Inc. *et al.*, 2009).

Figure 25. Volume-Delay and corresponding Volume-Accident curves

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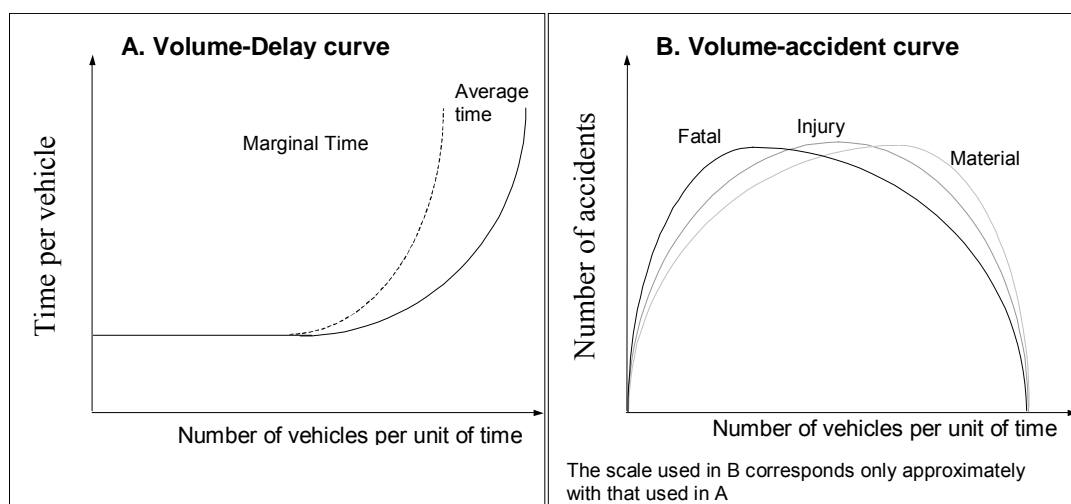
[88] Thus, in the U.S., the falling number of deaths (absolute and per capita) by cohort (Evans, 1993) can be explained by this effect and by the effect of the average rate of occupancy of vehicles. Driving experience is not taken into account. It is a notion best studied by more disaggregate methods as in Bolduc *et al.* (1993, 1994, 2012) where collinearity between age and experience might be more manageable than with more aggregate data.

[89] One can easily imagine, close to the origin, a different form whose angle defined by the abscissa and a straight line meeting the frequency curve implies first an increasing slope and later a decreasing one.

Figure 26. Relation between bodily injury accident risk and traffic density, Norway, 1974-1994
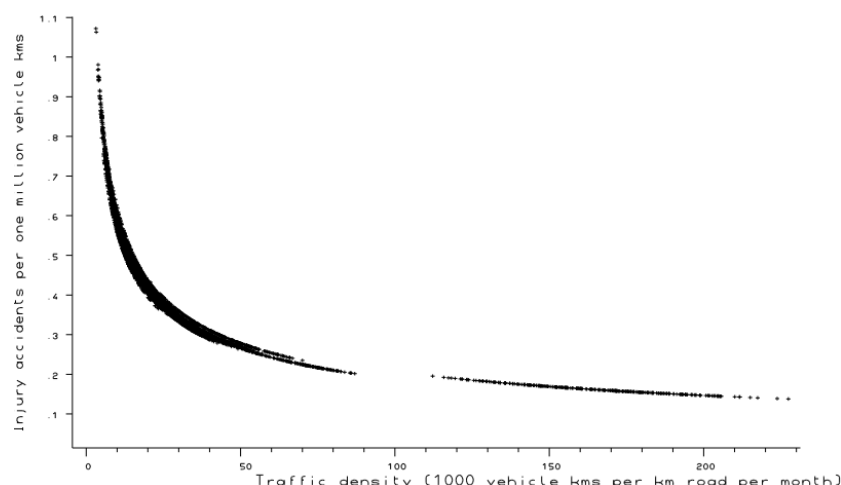
If Fridstrøm's elasticities were measured at sample means by a sophisticated non-linear flexible form model that readily allowed for the distinction between the effect of volume of traffic and the effect of the density of traffic, this crucial distinction is ignored[90] in simpler regression models such as Edlin & Karaca-Mandic (2006) that only explain the average cost of damage by density: they implicitly obtain a sum of the two elasticities estimated by Fridstrøm, the second of which is illustrated in Figure 26.

Figure 26 illustrates, even more clearly than the overall elasticity value of –0,42 can do, the impact of density on bodily injury accidents. As congestion is rare on the roads of the 19 Norwegian counties[91] from 1974 to 1994, the model no doubt yields results for the "free flow" part of the volume-delay curve shown in Figure 25. The "benefit of density" is the gradual reduction of the frequency of accidents per car-km represented on the B part of Figure 25 where, beyond the maximum, the absolute value even falls[92].

It is now up to researchers to determine, based on line F of Table 15 showing the extended model, the respective roles of the occupancy rate, traffic density and speed (without congestion and eventually with congestion). It seems possible to estimate those parameters found in equation F (its optimal form may of course not be logarithmic as assumed in Table 15), distinguishing not only between speed, traffic and traffic density[93] effects on fatalities but also on other categories of injured victims.

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[90] In Fridstrøm's model, distinct Box-Cox transformations of traffic and traffic density variables make it possible to identify both effects, which is impossible with a logarithmic form. Is is much more general than the model by Edlin & Karaca-Mandic (2006) which only has density and tries linear and strictly quadratic versions of that variable, a somewhat primitive specification in comparison with Fridstrøm's, which these authors have clearly not read.

[91] The source is Ch. 6, p. 45, Figure 6.2; the graph contains 4788 monthly observations on the 19 counties. The isolated observations found in the flat part of the curve, in the range of 110 to 230,000 cars-km per month, are for Oslo.

[92] In Part 2, we noted that the DRAG-3 model included an explicit reversed U-shaped curve for the frequency of fatal accidents and for the mortality rate. This makes the sign of the exposure variable vary according to the month.

[93] There is a conceptual difference between speed and density, even if they are both linked by a function on a given link, as in Figure 25 where the form of the reversed U-shaped curve varies with the severity of accidents.

Hopefully, this research hypothesis, by identifying separate effects for traffic, density, speed and occupation rate, might explain both for the 1972-1973 peak and the regional differences found in our countries. These differences indicate that the density/speed factor plays a role that may explain why population density is used as a classification factor among road types. Combined with the occupancy rate, this hypothesis can be called the "speed/occupancy conjecture".

9.3.4. The role of economic activities

In models of transportation demand, including demand for road use, the variables describing economic activity vary in precision and detail. Annual models favor the use of the Gross Domestic Product (GDP) or National Income as the general measure of economic activity. But such models tend to neglect the role of secondary activities closely correlated to GPD on a yearly basis. The effect of GDP on the demand for transportation is thus an imperfect representation of the exact impact of final and intermediary activities.

However, as soon as quarterly or monthly figures are used, the role of these various intermediary economic activities (in the input-output matrix sense) for any explanation becomes more interesting, as shown for instance by Foos & Gaudry (1986) and Blum *et al*. (1988) for the demand for road use in Germany. These studies show that all intermediary activities are relevant and that their specific elasticities are identifiable: the levels of intermediate economic activities across sectors vary considerably on a monthly or quarterly basis. The question that may then be asked is what a doubling of total (intermediary and final) economic activities implies for total demand for road use by people and goods.

The answer provided by the monthly meso-economic models of the DRAG family, where intermediate activities have been most extensively distinguished, is clear: if economic activity is doubled while other factors such as rate of motorization and prices remain the same, the demand for road use also doubles. This is demonstrated in the Quebec application of DRAG-2 (Fournier & Simard, 2000) where 18 economic activities were taken into account (9 involving cars and 9 involving trucks). This was also the case of the I-DE model for Spain (Bernardos & Arenas, 2008; Aparicio *et al*., 2009) where 8 economic activities were distinguished. Doubling **[Â]**, at a given congestion level, approximately doubles **[DR]** in short-term monthly models.

9.3.5. Expected value of indicators conditional on activity and car occupancy

What can be expected at best? As mentioned earlier, car occupancy rates are getting close to 1,00 and will soon stop falling. But as long as the economy keeps growing, the total demand for transportation and the road share will play an important role. *Ceteris paribus*, the hard core nature of these two factors is enough to seriously question the realism of the goal of a division by 10 of the number of fatalities in France.

9.4. Uncoupling transport from the economy in the medium term?

The most difficult task modelers have to face in regard to the levels of economic activity and the demand for transportation is to propose forecasts for the medium term. Given the fact that this problem is an issue of critical importance and that it has not been studied in depth yet, the following questions arise: which long-term trends will affect the demand for transportation, particularly the demand for road use, in France and elsewhere? Do the trends and possibilities of uncoupling transport from the economy vary according to whether we study people or goods? A few studies made in France recently (*e.g.,* CGPC, 2006) forecast a partial but small

uncoupling: these are based on an elasticity of mobility with respect to GDP slightly lower than 1.0. Let us look at this question, drawing extensively from Gaudry (2009).

9.4.1. Economic growth and the total demand for transport

Contrary to the total demand for energy, the total demand for transport[94] (all modes included) is hard to dissociate from economic activity in the sense that one might hope for a strong decrease in the number of person-km and ton-km per marginal unit of GNP. It could not easily match the reduction in energy use per unit of GNP that followed the rise of the price of oil in October 1973 (when OPEC was created) and once again in 1980 (when OPEC was revived).

This close secular relationship between economic growth and transport demand, implicit in Figures 27 and 28 for person-km/day and ton-km/year, will remain strong unless the favorable trends in fuel prices and regulatory obstacles to transport dramatically change.

And then we still have to clearly differentiate between transporting persons and moving tons of goods, either multiplied or not by kilometers traveled. Other factors may also come into play. For instance, recent figures show that total tons lifted (carried) in the European Community (15 countries) has declined since 1970, but that, at the same time, the number of tons-km has increased faster than the GDP of that Community (Joignaux *et al.*, 2002). If we are to better understand this uncoupling, the reconciliation of models of tons lifted and of ton-km moved, of spatial cross analyses and national aggregates, will be needed.

Figure 27. Daily distance covered per person, France, 1800-1990 (Grübler, 1990)

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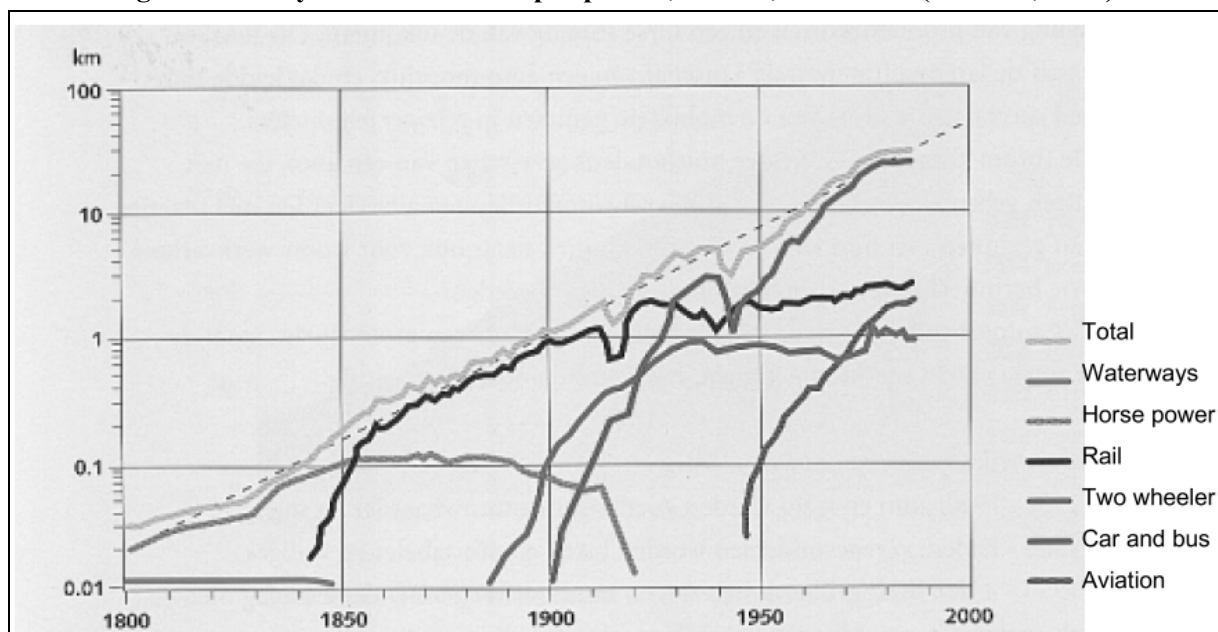
[94] To confirm this point, we would need to discuss further units of measurement: people or tons, kilometers. The idea proposed by Zahavi (1979) and reiterated by Marchetti (1994), citing data from Grübler (1990) on person-km and messages sent in France, is tantamount to an assumption of a strongly diminishing utility of time after an hour on the road. It implies that faster means proportionately further and implies a corresponding surface change for urbanized areas. In recent successive French national transportation surveys (1978-1979; 1993-1994) the average time spent per adult in daily travel was slightly more than 20 minutes. However, the average distance traveled by plane doubled from 600 to 1 200 km per flight.

### 9.4.2. Zahavi's conjecture on the willingness to travel

Zahavi's conjecture pertains only to travel time: the willingness to travel would decrease abruptly after a one hour per day "limit". The global numbers shown in Figure 27 seem to indicate, simultaneously with an extraordinary increase in the distance traveled, the presence of an asymptote in the sense that, as income rises and transportation technologies (and regulation) evolve (including cost), the overall time spent per trip does not seem to be affected. The distribution between modes of transportation (slow and rapid) and the distance traveled[95] are the two components that do indeed change in easily measurable ways.

This fact, however, does not apply to the United States where the average time traveled tends to increase with urban GDP (Crozet & Joly, 2004). This could be explained by the high gradient of land rents in North American urban sprawl: longer commuting time means relatively better access to cheaper land and housing than it does in Europe or in Asia. Consumers are then led to buy larger lots, even small ranches (*e.g.* outside Denver), all the while knowing that doing so increases commuting time. This option is not available in more populated countries where the density of population produces a flatter slope of the cost of land from center to periphery (of the rent gradient). Such differences between Europe and North America are compatible with the fact that, ever since the beginning of the 20th Century, the CBD core to suburb gradient has decreased everywhere, in both Europe and America.

9.4.3. What of goods?

No evidence has yet been presented on a `saturation" level of the total demand for transporting goods in relation to economic growth. The longest known series of data on the subject are the ones presented in Figure 28 (Sauvant, 2002). They cover the closing of coal mines and the passage to nuclear energy in France. Apart from the exclusion of two wartime periods, no information would lead us to think that the trend (1.7% per year, exactly as for the total in Figure 27) has changed.

Figure 28. Secular trends of freight traffic in France
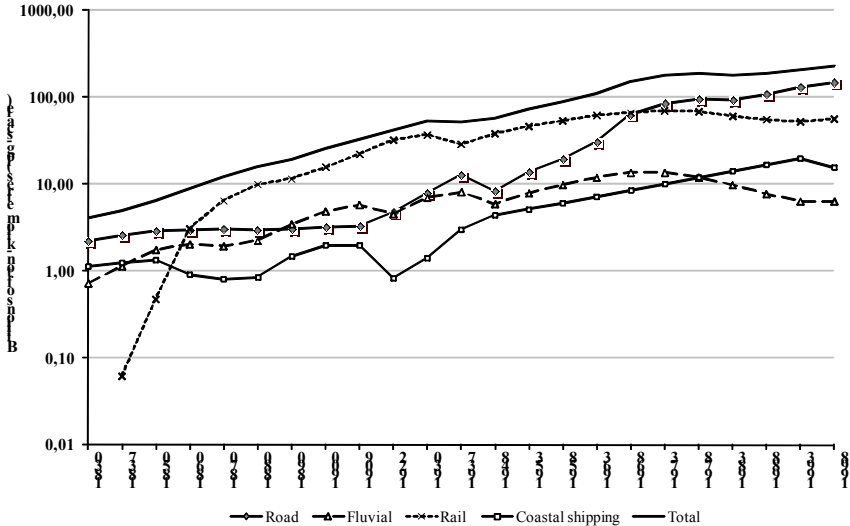
This is surprising to the extent that the share of the service sector in the economy keeps growing. Chances are that we have little if any data on the goods consumed by the service sector that can be used in the input-output analyses originally designed for goods (Leontief,

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[95] For example, the average distance traveled by plane has doubled in France during the period between the last national surveys i.e., 1978-1979 and 1993-1994. This distance went from 600 to 1 200 km per flight.

1941) and later spatialized (Moses, 1955) in ways that are still used today in transport modeling (Cascetta & Di Gangi, 1996). If we wish to understand why an electronic office in New York today managed to double its consumption of paper between 1990 and 2000, we need to refine our analyses…

9.4.4. The Luddite instinct: communications as substitutes for transportation

What should one expect from communications? We like to think that the more communication infrastructure we have, the smaller the need for transport. This assumes that more of one input means less of the other or that more capital equals less labor. On this point, the past 250 years have proven that the reverse is the case: the amount of capital per worker has been multiplied by more than a factor of 10 and employment has also grown enormously. Let us look at Figure 29 from Grübler (1990) and see where history resides.

One look at that figure is enough to put aside the assumption that better communications result in a decreasing demand for transport. For the past three centuries, no notable downward trend in demand for transport has occurred following technological innovations in communications. None, among the Royal Postal service, the telegraph, telex, fax machines or the Internet, have produced a *perceptible* effect on the aggregate demand for transport (of both people and goods). Teleconferencing (2D) was also supposed to curb the demand for travel, but it hasn't done so, in spite of its growing popularity. It has now evolved into 3D teleconferencing. Will this really affect the demand for transport?

But why do two modes of putting people in relation appear to Luddites and others as substitutes but in fact behave in the aggregate as complements? It is possible that, when the question is asked for the first time, the set of economic activities [Â] is assumed known and fixed, but that it changes when relative prices change ? How might this make sense?

Figure 29. Daily distance covered and messages sent per person, France, 1835-1990
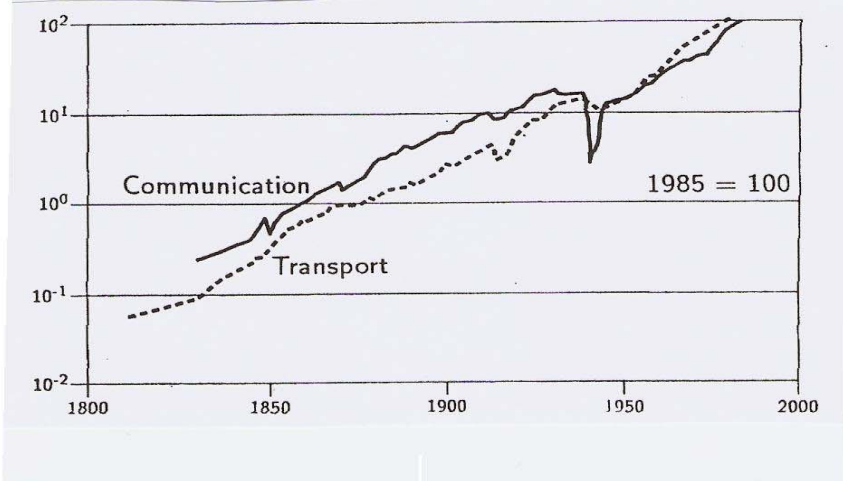
### 9.4.5. Implicit corollary on communications and transport as inputs

If there is a relation between transport and communications, it clearly seems to be one of complementarity rather than one of substitution — at least in figure 29. It is possible that, even if communications were to cost nothing at all, the demand for transport would not stop increasing. To understand why, let us study Figure 30.

Extracted from Gaudry (1998), Figure 30 represents the classic demand input framework. First replace capital and labor inputs with transport T and communications C at levels required for a given economic activity represented by a classic isoquant; and then focus on new economic activities resulting from lower communications costs. The initial budget of the new activity Â is null because the minimum level of communication required is not accessible at this price. But a price drop of C changes the demand for communications and the demand for transport together from point 1, twice null, to point 2, twice positive, *i.e.* now feasible due to the price drop.

Transport and communications, on the surface of it or short-term, seem to be substitutes. But on the long-term the means of bringing people together behave, as aggregates, rather more like complements. We implicitly assumed that the sum of all economic activities was unchanging. But in fact, companies frequently move the location of their facilities or departments, from accounting to production[96]. In addition new economic activities emerge: university professors become dissertation advisors to foreign students afar, something that could not be done when communication costs were high. But this also creates a new demand for travel.

Figure 30. New activity Â, resulting from a fall in communication relative to transport cost
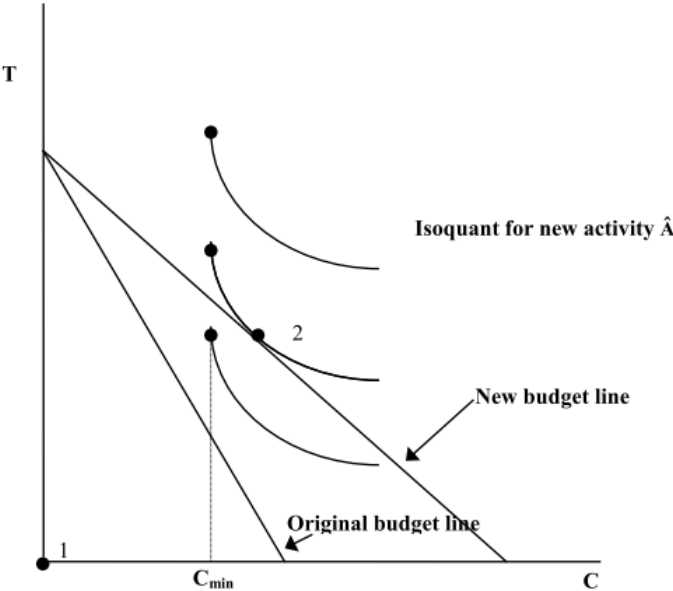
In conclusion, it seems that we cannot count on communications to solve our transportation problems. Communications will continue to expand and grow but will always remain complementary to transportation; the same way capital and labor are complementary.

9.4.6. Expectations from uncoupling and from the demand for road transport?

What can be expected from uncoupling? And from road demand? Actually, nothing. If the costs of transportation do not rise, and if regulation does not curb its development, the demand for the transport of people and goods will keep growing with the economy. And new communication technologies and tools will remain gross complements to transport.

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[96] This unbundling is nothing new. For instance, workers nowadays seldom sleep at the plant, but it was often the case one hundred years ago, as it is in China.

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Conclusion: some hard questions for road safety experts

10.1. Unconnected research pebbles or dotted stream paths after Smeed and Weber?

The threads running through aggregate and discrete models, distinguished in this survey are presented as somewhat interconnected research streams but this continuity is, for a part, a retrospective construct because known milestones of aggregate modeling, such as Peltzman (1975), fail to mention any of the most obvious seminal antecedents (*i.e.* Smeed, 1949 or 1968; Smeed & Jeffcoate, 1969), despite their obvious relevance and use of the same log-log format on similar variables; and because we have yet to find a major discrete accident frequency model referring to the foundation work by Weber (1970, 1971), in this case a neglect bordering on indecency in papers using the same approach, variables (notably past accident, infraction, or criminal records) and even the same Poisson estimator.

As both Smeed and Weber are available in mainstream journals, their lack of recognition by so many must be imputed either to serial accidental memory failings or to the loss of the ability to do develop, or consult, bibliographies on road safety such as Haight's (1964) who, for one, lists about 40 of Smeed's articles — Haight could recognize predecessors.

10.2. Latent conclusions and unanswered questions

Our bringing together, in the same survey, aggregate and discrete models made us very aware of a number of unanswered questions that could be put to road safety experts. We select a few here, already found in the state-of-the-art triplet[97], for further comment.

10.2.1. From peak to valley or plain? A speed-density-vehicle occupancy conjecture

It is pointed out in Table 2 of Part 1 that a *Meadow/Matterhorn/Cervin*-shaped peak in road fatalities happened almost simultaneously in many advanced economies: remarkably, 18 countries reached their maximum between 1970 and 1973 — 10 of which jointly (to the month of August) in 1972. These 18 countries have all seen a downward trend since, except perhaps for the U.S. which deserve some comment.

As seen on Figure 1, the U.S. toll evolved from the maximum of 1972 (at 54 589[98]) downwards until a (third) local minimum in 1992 (at 39 235). It then climbed continuously until 2005 (at 43 550) and fell again, between 2006 and 2010 (at 32 885): there remains some doubt as to whether this last bulge is strictly consistent with the previous trend and, the economic cycle taken into account, whether the U.S. are still in step with the remaining 17.

The peak of 1972 was noted early, for instance by Haight (1984), and the subsequent downward slope (or similar ones) has been cause for self-congratulations in many countries; but, in the absence of an understanding of the causes of the maximum[99], it is hard to decide whether compliments are deserved. It is harder still to forecast the future, taking due account of a slowing down of improvements in many of the 18 countries and in closely related ones

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[97] We refer to these as Part 1, Part 2 and Part 3 without further qualification.
[98] The order of magnitude of the number of American soldiers killed during the 10 years of the Viet-Nam War.
[99] Except for strict statistical issues on the measurement of fatalities.

like Sweden (see Figures 22 and 23 of Part 3) and the United Kingdom, which both peaked slightly before the reference 18 did.

Unfortunately, simply working with per capita instead of absolute fatality values does little to change this time profile question because population varies much less fast than road fatalities rise or fall, even in countries where population growth has been significant[100]. It needs to be asked whether the countries clouded in the "mystery of 1972-1973" or nearby are approaching a minimum or a plain and whether the U.S. trend still parallels that of the other 17, or not.

For the U.S. to still be in step, the local maximum of 2005 must result primarily from an economic expansion ending clearly in 2006 with the collapse of the housing boom[101], rather than with the freezing of money market liquidity (2007) or the collapse of Lehman Brothers (2008). And the analysis of fatal accidents gives reasons to think that this is the case.

Figure 1. Yearly road fatalities in the USA 1965-2010
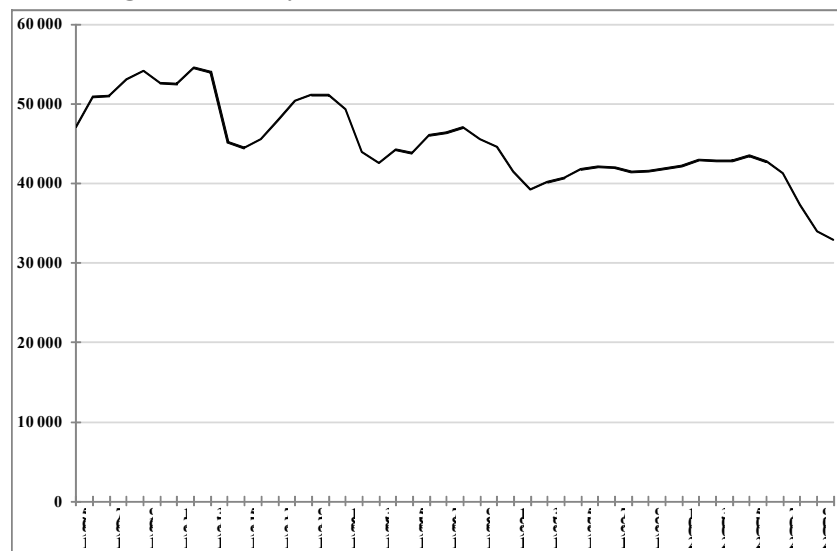
It has indeed been noted by Sivak & Schoettle (2010) that, between 2005 and 2008, last year for which detailed data were available to them, U.S. road fatalities dropped disproportionately in peak AM and PM time periods, in accidents with 2 or more fatalities, in accidents of the less than 25 years of age and in accidents for those with 2 or more previous accidents over the period. These indicators suggest an extremely severe recession creating unemployment in lower economic groups[102], notably among the young.

As a sudden return to boom conditions of 2005 would imply an increase of about 11 000 fatalities per year, it is tempting (in the absence of a more sophisticated analysis) to treat the maximum of 2005 as primarily caused by the economic cycle: perhaps is the "fourth pillar" of

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[100] In Israel, the highest number, 702 in 1974, fell slowly to 314 by 2009 despite significant population growth.
[101] As claimed by Krugman (2012).
[102] Lower economic groups tend to have higher accident rates. This almost universal finding comforts the view that the generally favorable role of educational attainment levels in the explanation of accidents essentially results from a selection bias, to the extent that the sitting power required for studying differs from that required for driving and implicitly selects individuals with specific behavior towards risk or "accident proneness". If educational attainment variable selects low risk takers, it may not come as a surprise that drivers of light utility vehicles have relatively high accident rates.

road safety analysis dictating fluctuations again (in particular between 1992 and 2010) and does the trend remain, as before and elsewhere, downward and perhaps even unbending.

To make sense of the peak that occurred some 40 years ago and of the current evolution, we propose in Part 3 (Table 15, Equation F) the *Speed/traffic density/vehicle occupancy rate Conjecture*, an extension[103] and reinterpretation of the Smeed model. It is testable, even if experimental strategies are not yet elaborated for discrete models[104] where the multinational datasets useful to answer the question are for the moment unknown. In our view, this opens up a research topic.

10.2.2. An asymptotic plain made up of hard core strata plus randomness?

First, and as already alluded to, there are in many countries — including Sweden and the United Kingdom — indications of a slowing down of the rates of improvement in morbidity and mortality rates, but the stratification of any asymptote remains vague and uncertain[105]. In addition to the evolution of explanatory factors the effects of which are thought to be identifiable, and still to matter on the way towards any limit, there appear to be hard core accidents "immune" to measures or "incompressible" (Stipdonk *et al.*, 2005). This points to the possible existence of a natural rate of road mortality, a concept we discuss and contrast with that of conditional expected road safety performance. But the distinction between *bottom-of-the-barrel* unresponsiveness in drivers, *uncontrollable factors* and the *randomness level* inherent to accidents is however not easy to make. Consider the first two.

A. The return of accident proneness and the move towards individualized pricing

We present in Part 1 (Figure 7.B) the extraordinarily Weberian results outlined by Krupp (2005), based on Schade & Heinzmann (2004) . Working with very large German samples, they showed that, although relative accident rates per kilometer driven are known to differ by a factor as large as 7 or 8 across age-sex groups (as represented in Figure 7.A), the relative individual accident risk during any period is indeed a function of the number of past infractions (as Weber taught us 40 year ago) but that difference happens to be *strictly independent from age or sex*. Risk-taking individuals could therefore be life-long bad apples[106] … because their relative badness does not depend on age[107] or sex differences: equality of the sexes at last — of their relative offensive behavior! A stunning result.

This sort of finding implies that some apparently effective safety measures, such as speed-radar photo enforcement (SPE) in France — understood to cause so many losses of driving permits that perhaps as many as 150 000 individuals have recently been added to the ranks of those who drive without them — pose real sustainability questions if the consequences cannot

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[103] An ideal topic for the Reuben Smeed Centenary recently advertised by University College London.

[104] An exploratory strategy for models based on aggregate data is outlined in Gaudry & Gelgoot (2002).

[105] Despite this, the 2011 White paper of the European Commission aims at a 50% reduction in fatalities by 2020 and approaching 0 in 2050.

[106] For instance, the Jun *et al.* (2011) study based on longitudinally-measured GPS speed data of light-duty vehicles found that "at most times (spatially and temporally), drivers who had crash experiences tended to drive at higher speeds than crash-not-involved drivers except in freeway travels during a.m. peak hours. Crash-involved drivers also showed higher tendencies of non-compliance with the posted speed limit." Strictly Weberian again.

[107] This result is consistent with the finding by Bolduc *et al.* (1993, 1994, 2012; Table 11) that the effects of various *particular* past traffic code violations on accident probability vary across the four age groups. The samples used by Schade & Heinzmann are much larger and structure vilolations differently.

be managed. It also means that measures progressively eliminating[108] the cross-subsidies across individuals found in insurance systems[109] — and forcing insurance prices towards individualized experience rating — will bring out so much variability in safety performance across individuals that political pressures could build against price structures changing from 7 or 8 age-sex risk categories per kilometer driven towards 35 or 40 experience rated neutral categories — devoid of any age-sex discrimination because strictly experience-rated. Removal of the protection of averages and price caps on insurance prices will not be easy because it could price many out of the market or into jail.

Concerning capacities linked to age and sex, insurance pricing is moving away from group justice (based on the first moment of accident risk linked to age and sex) towards individual justice (based on the second and third moments measured by experience rating). Concerning alcohol consumption however, legal blood alcohol concentration (BAC) levels (assumed to be monotonic indicators of the first moment of accident risk[110]) are imposed at the expense of individual experience rating (higher moments of actual performance while impaired). "Group justice" is avoided through experience rating legislation in one network access dimension and re-established in another through BAC legislation forbidding experience rating. Why are the moments of accident risk not treated equally across explanatory factors?

B. Are there putty factors that offer no clay handle to policy makers?

Let us consider some representative examples of the numerous interesting matters left out of the state-of-the art, focusing on interesting facts linked to the difficulty of fighting inattention and fatigue, factors which might be part of the "incompressible" accidents.

Start with run-off-the-road (ROR) incidents. The life expectancy of someone standing on the side of tolled French highways is said by their managers to be about 20 minutes[111]. And in the U.S., the single greatest category of highway vehicle crashes is indeed run-off-the-road (ROR) incidents. Can anything be done?

One known option is shoulder paving, recognized as a positive countermeasure to reduce a shoulder drop-off hazard: significant material differences and elevation changes in shoulder edges pose a potential safety hazard when a vehicle leaves the travel way. But what happens after all shoulders are paved? Liu & Ye (2011) have shown that (i) the most influential factors in the occurrence of single-vehicle ROR crashes were the factors "driver inattention," "driver was fatigued," and "driver was in a hurry"; (ii) the odds of being involved in ROR crashes for the vehicles equipped with neither ABS nor ESC were 2.1 times greater than the odds for the vehicles equipped with both ABS and ESC. So some inattention, lack of vigilance and fatigue can be partly compensated for, assuming that car equipment is not a proxy for driver characteristics and that drivers do not spend the gain in increased risk taking.

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[108] An example is that of the European Court of Justice that outlawed discrimination on the basis of sex in June 2011, a movement that should logically lead to the removal of age-based discrimination in the future. But what will happen if, following Weber's specification, risky road behavior (speeding, running red lights, excessive blood alcohol concentration) is shown to be correlated with other forms of criminal behavior? Will a criminal dossier be accepted as an insurance pricing criterion because it is demonstrably experience-rated?

[109] For instance, in many places, such as Quebec, the insurance *premia* for motorized two-wheel vehicles are capped for political reasons and motorcyclists are, relatively and absolutely subsidized by other drivers.

[110] Whether alcohol consumption is monotonically related to accident risk is another question.

[111] Interviews of 3500 drivers at toll barriers of a French highway in July 2011 revealed that 42% of them had driven on the noise-producing markings of highway shoulder edges during the year, 16% because of somnolence and 71% by distraction (Negroni, 2011).

A second case is that of pedestrian accidents. In the USA from 2005 until 2009, 12% of road fatalities were pedestrians. In 61% of the cases (and in all cases of frontal collisions), street crossing pedestrians were hit by drivers who were going straight with no visual obstruction and only 13% of those hit the brakes in those fatal impacts, as well as in non fatal ones (IIHS, 2011). Hard to model again …

A third example is that of truck involvement in fatal accidents. In the U.S. from 2004 until 2008, the other vehicle crossed the center line of the road and struck the truck head on in 11.0% of fatal involvements of trucks (Jarossi *et al.*, 2011). In addition, in 2009, those large trucks were four times more likely than other vehicles to be struck in the rear in two-vehicle fatal crashes (NHTSA, 2011). Are large trucks attracting cars?

And do these three factors belong to an "almost uncompressible" category or to randomness?

10.3. Puzzle: making sense of the popularity of conditional severity models

In addition to neglected questions, the state-of-the-art also puts aside comments on the distribution of safety topics in journals. One puzzling development is the growing popularity of discrete severity models, documented in Part 2 (*e.g.* in Table 12), if only because this dimension is somewhat secondary to that of frequency in many aggregate models. It is clear from authors' comments that they relate more closely to their frequency than to their severity dimensions (morbidity and mortality), and that they have many anticipations and intuitions concerning frequency but fewer with respect to severity, if they make the distinction at all — even Peltzman (1975) did not. Imagine the difficulty of defining *a priori* distributions of values for severity models, as opposed to frequency models: uniform or Jeyffreys distributions[112] could be favored more often in the former than in the latter case!

To make sense of this growing practice, we argue here that conditional severity models are in fact interesting for authors because researchers implicitly consider that they tell us something about frequency, the dimension they relate more easily to. One must therefore ask how much conditional severity actually tells us about frequency and whether authors can be forgiven for interpreting their results as they sometimes do — slipping from the likes of "*variable X_k influences the conditional probability of bodily injury accidents more than the conditional probability of material damage accidents*" to "*variable X_k influences the probability of bodily injury accidents more than the probability of material damage accidents*". Can the "conditional" qualification ever be safely dropped?

To answer the question, we borrow the Quasi-Direct Format from Part 3 and, instead of multiplying a model of total transport demand for all modes by a mode split model to obtain the demand by mode, we multiply a model of total accident frequency A by a conditional severity model explaining the probability of each severity category p_c: the result of the multiplication is naturally the number of accidents by severity category A_c:

(1-A) $$A_c = [A]\{p_c\} \qquad c = 1, \dots, C$$

where the multiplied models may be generally explicated as:

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[112] The latter allows for a proper posterior distribution.

$$(1\text{-}B) \qquad A_c = \Big[f_a \big(X_1, ..., X_k ; I \big) \Big] \Big\{ U_c \Big/ \textstyle\sum_{s=1}^{s=C} U_s \Big\} \qquad\qquad k = 1, \dots, K,$$

with the X_k variables understood as ordinary determinants of total accident frequency (*e.g.* vehicle-km, weather, *etc.*) and the variable I denoting Expected Maximum Insecurity (EMI), an inclusive value constructed from the denominator of the split model, assumed to be a Linear Logit where the U_c terms associated with each severity category are of the form:

$$(1\text{-}C) \qquad U_c = \exp\Big(\beta_{0c} + \textstyle\sum_k \beta_k X_{ck} \Big) \qquad\qquad k = 1, \dots, K.$$

and the X_k variables may or may not all be present in both model components.

In this structure, the coupling of the split and total models is realized by the Expected Maximum Insecurity (EMI) index directly inspired from the Expected Maximum Utility of transport modes: the logarithm of the denominator of the split model, or *logsum*, therefore summarizes the worst that can be expected in terms of insecurity. This EMI construct has been used in a disaggregate accident frequency model by Gaudry & Vernier (2000).

The product of component models implies that the direct elasticity of the resulting number of accidents of a certain severity category A_c with respect to an explanatory variable X_k is given in the most general case (with X_k present in each component and in the EMI index) by:

$$(2\text{-}A) \qquad \frac{\partial A_c}{\partial X_k} \cdot \frac{X_k}{A_c} = \left[\frac{\partial A}{\partial X_k}\frac{X_k}{A} + \frac{\partial A}{\partial I}\frac{I}{A} \cdot \frac{\partial I}{\partial X_k}\frac{X_k}{I} + A\frac{\partial p_c}{\partial X_k}\frac{X_k}{p_c} \right]$$

or

$$(2\text{-}B) \qquad \left\{ \begin{array}{c} \eta\,(A_c, X_k) = \underbrace{\eta\,(A, X_k)}_{(A)} + \underbrace{\eta\,(A, I) \bullet \eta\,(I, X_k)}_{(B)} + \underbrace{\eta\,(p_c, X_k)}_{(C)} \\ \underbrace{\qquad\qquad\qquad\qquad}_{(E)} \\ (F) \qquad = \qquad\qquad\qquad (E) \qquad\qquad\qquad\qquad (D) \end{array} \right\}$$

When a variable X_k fails to appear on its own in the total accident frequency component, assumed for instance to be of logarithmic form, term (A) is null and, with β_I identifying the coefficient of the *logsum* (the severity index induction elasticity (B)), (F) reduces to:

$$(3) \qquad \frac{\partial A_c}{\partial X_k}\frac{X_k}{A_c} = \big\{ \beta_I \Box \beta_k X_k p_c \big\} + \big\{ \beta_k X_k (1 - p_c) \big\} = \big\{ \beta_k X_k \left[p_c (\beta_I - 1) + 1 \right] \big\}$$

where it is clear that, because X_k and p_c (the probability or share of accidents of category c) are positive, the sign of β_k in the conditional severity model part (D) is also the sign of the elasticity of accidents of category c, (F), unless $p_c(\beta_I - 1) < -1$. Of course, insecurity (or risk) induction elasticities β_I would normally be negative and much smaller than unity[113], so this result is unlikely. Dropping the word "conditional" and reinterpreting signs in the severity component as indicative of the direction of effects on frequency is therefore reasonable in those cases.

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[113] In passenger demand models, the elasticity of total travel demand by all modes with respect to the Expected Maximum Utility of modes is of the order of one tenth.

When the variable X_k also appears on its own in the generation component, sign reversal would require that (A) be both of a different sign and larger than (B)•(C) + (D), *i.e.* larger than $\left\{ \beta_k X_k \left[p_c (\beta_I - 1) + 1 \right] \right\}$. To see how this can occur, consider the impact of snowfall on fatal accidents, which are a very small part of all accidents. It is possible for (A) to be positive and of the order of 1 or 2 (because total accidents increase much with snowfall) while β_k [and (D)] are negative but $p_c (\beta_I - 1) > -1$ due to the minute share of fatal accidents. In such cases, where (A) is large but (D) is small and they are of opposite signs, dropping the word "conditional" is not possible. And sign inversion between total frequency and conditional severity effects is an insufficient condition for sign inversion from (D) to (F) because the absolute values of elasticities and the result from the coupling product (B)•(C) also matter.

The sign and elasticity size conditions for slipping from conditional severity to frequency can therefore be pinned down. The formulae for cross-elasticities or more complex models admitting of Box-Cox transformations of variables are straightforward and deserve full elicitation in other quarters.

10.4. References

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