Analysis of road mortality in digital age using Bayesian ecological model: The case of Tunisia

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Abstract – While awareness of the public health burden represented by road insecurity is recent, the idea that it is developing countries, particularly in Africa, that experience high road mortality, is older. In this context, our paper aims to propose solutions for the decision-making process on road safety in Tunisia through the study of road mortality rate perceived under two respective angles: population density and geographic unit affiliation. The modeling and analysis work will allow identifying better the respective weight of the factors associated with road mortality. Methodologically, our recourse is so the Bayesian ecological regression model to meet our cited goal. The model parameters are adjusted by Gibbs sampling. Econometrically, the hypothesis related to the influence of population density on road mortality has been proved. A new ranking of Tunisian governorates, according to their road mortality rate standardized by population size, is illustrated. The variation in road mortality risk is the highest at the delegation level but is the lowest at the district level and the governorate level, which proves the existence of other responsible factors observed at the regional level. An estimated elasticity of -0.25 at the district level means that a 10 % increase in population density can cause a decrease of 2.5 % in the occurrence of road mortality. Mapping the Bayes relative risk can assist the identification of regions that can be targeted by the national policy. Consequently, this study shows that the analysis models can provide a better overview of the road safety situation and a robust tool for decision-makers.

Keywords – *Road safety policy; Regional analysis; Road mortality; Population density; Bayesian method*

1. INTRODUCTION

Improving road safety is a pillar of sustainable mobility and one of the international challenges (Yerpez, 2004). But it is an urgent necessity, especially for developing countries that are paying a heavy price for road insecurity (Muhlrad; 2010). Road safety is a major problem for these countries in terms of the loss of human lives that it causes and the socio-economic costs that it generates. In most developing countries, road safety is not a priority for governments. According to the African Development Bank (2013), these countries, particularly in Africa, suffer from a lack of information and capacity in this sector. The World Health Organisation (WHO), specifies that the number of road deaths worldwide remains unacceptably high, with an estimated 1.35 million deaths each year and are valued to cost 3 percent of the GDP globally, more than half of whom are vulnerable road users: pedestrians, cyclists and motorcyclists.(WHO, 2018). Traditionally, road accidents have been treated as isolated incidents caused by bad drivers and as an side effect of increased mobility. Consequently, responsibility has been attributed to individual road users whose behavior government responses have required to influence through education and control. This approach to road safety governance has been questioned (Hysing, 2019). Governments are urged not only to influence drivers but also to attribute safety responsibilities to system designers, including vehicle manufacturers, road administrations and other transport professionals (Elvebakk 2007; McAndrews 2013).

As in other developing countries, Tunisia's mobility situation has deteriorated. Poorly accompanied intensification of mobility has led to problems reflecting the failure of the transport system and its inability to respond quantitatively and qualitatively to the increasing needs of users, as well as to the country's economic, demographic and urban growth (Ministry of Transport of Tunisia, 2013). Furthermore, Tunisia has experienced an intense coastalization phenomenon, as a result of a high concentration of the population and the majority of development activities. This concentration is the result of territorial planning and the development approach adopted since independence, which has favoured the coastal fringe to the detriment of inland areas. Indeed, more than 70% of the Tunisian population lives there and about three-quarters of the road, industrial and tourist infrastructures are located there (Castel et al., 2014). Even in the same region, the population is more concentrated in communal than non-communal urban areas. These two phenomena of coastalization and urbanization effectively reflect public policies that have led to the isolation of the entire hinterland, aggravated regional imbalances and resulted in inequalities in access to public services (education, health, transport, etc.). A set of elements that also directly or indirectly influence road safety (Chelbi, 2010). Today, Tunisia is in the process of becoming a democracy. So, it would certainly be useful to pay particular attention to the road accident toll in Tunisia, and more particularly to the road mortality situation.

In Tunisia, citizens always live a dramatic situation, with a daily average of more than 21 accidents causing more than 32 injured and over 4 deaths[1] and with socio-economic costs which represent nearly 190 million dollars annually (WHO, 2013). It is not surprising that more attention and resources are being devoted by decision-makers. In 2013, with 24.4 deaths per thousand inhabitants, Tunisia is the third largest middle-income country and ranks 2nd in the Maghreb (WHO, 2015). On a regional scale, with 24.4 road deaths per 100,000 inhabitants, Tunisia ranks ahead of Algeria (23.8 deaths per 100 000 inhabitants) and Morocco (20.8 deaths per 100 000 inhabitants) but far behind Libya, which has 73.4 deaths per 100 000 inhabitants. This figure is explained by the large number of motorists killed by road accidents, according to the WHO. Indeed, out of the 24.4 deaths per 100000 inhabitants on the roads of Tunisia, 11.8 are drivers of private cars, or almost half. Tunisia is ranked 8th in Africa in terms of motorist fatalities, behind Libya, Niger, South Africa, Namibia, Botswana, Zambia and Congo. However, in the Maghreb, Tunisia is the first country in terms of motorcycle deaths (5 deaths per 100,000 inhabitants in 2015) and the second for pedestrians (behind Libya) and the last for cyclists (0.6 deaths per 100 000 inhabitants). In view of these data, Tunisia is considered a dangerous country with regard to road risk (Ouannes, 2016).

Nowadays, the National Road Safety Council meets once a year to give recommendations and many actors intervene in order to contribute, in one way or another, to the road safety improvement process. But nothing is done due to the lack of political will and the absence of a clear national policy for road safety (Bouhamed, 2019). Hence, each actor acts on his side without any coordination and therefore without real effects. The contribution of this article consists in analysing road mortality and statistically assessing the effects of spatial disaggregation and demographic specificities in Tunisia on institutional road safety management. Following this approach, this work would help decision-makers (national, regional and local) to better understand the factors associated with accident severity and to develop an appropriate and effective public policy for road safety in Tunisia (Papadimitriou and Yannis, 2014).

In this work, we base ourselves on an ecological Bayesian spatial model proposed by Ekslerand his co-authors (2008). This model replaces the simple spatial analysis by a multi-level analysis due to its advantages. In fact, it allows producing correct estimates compared to the single-level model estimates. Bayesian modelling techniques often use a Markov Chain Monte Carlo (MCMC) adjustment procedure in order to estimate the distribution of all model parameters. Traditional methods such as Gaussian and Poisson regression models are deficient. This has given rise to Bayesian methods that have shown their success, particularly in favour of epidemiological studies. They allow contextual data to be processed with unmeasured confounding factors and their spatial autocorrelation. (Elliott, et al., 2000), (Elliott, et al., 1992). Road safety is a multisectoral and transversal field, which concerns the different territorial scales. According to Guilbot (2009): *"The confrontation of points of view and the sharing of knowledge offer a more "panoramic" vision of the different modes of road safety management; each intervention constitutes a chapter of a piece that only makes sense when all the elements can be articulated".*

Road safety research often focuses on the national and/or local level. It is true that the national accident analysis makes it possible to give an overview, to evaluate the issues at national level and to judge the evolution of the repartition of road accidents in time and in space. As for the local road safety analysis, it makes it possible to define the policies of local authorities in terms of combating accidents, which are often high in number, particularly inside urban areas. Nevertheless, between these two territorial scales, the regional analysis of road safety is generally masked and lacks affinities. This study is therefore distinguished by its particular interest in the regional analysis of road mortality in Tunisia, which not only makes it possible to refine and better clarify the national vision on road accidents, but also to consolidate and complement the national road accident file published by NRSO.

This document is organized as follows: first of all, we highlight the theoretical foundations necessary to understand the key concepts of our research. Then, we present the data and variables used to run the adopted model. The motivation for these choices will be discussed. Finally, Part 3 develops the analysis of the results and will be finalized with a conclusion and perspectives that will lead to the launch of further multidisciplinary studies.

2. LITERATURE REVIEW

Improving road safety is a key objective for many countries. As a result, several studies are interested in analysing and improving the level of road safety. These studies differ both in the issues addressed and in the data used and the method used. Indeed, with regard to the spatial analysis of road accidents, various works exist in the literature such as the regional analysis of variations in road risk.

2.1 Analytical framework

Throughout history, space has always been considered the support of social practices and places of exchange between people (George and Verger, 2013). There is always a close link between demographic change, mobility needs and the organisation of

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[1] According to the National Road Safety Observatory (NRSO) of Tunisia (http://www.onsr.tn)

geographical space. The space component has been developed since the 1980s (Thomas, 1996). We have identified some regional analytical work that has been reported in the scientific literature (Clark and Cushing, 1999). These studies often involve a small sample of countries and do not take into account structural and cultural differences between different regions, resulting in heterogeneous mobility conditions. The regional analytical approach to road mortality risk has so far received little attention. This theme has often been referred to by researchers as a health problem, taking into consideration the victim's place of residence instead of the accident site (Shaw, et al., 2000). However, the work of Lassarre and Thomas (2005) was the first European-wide descriptive analysis of road mortality risk based on regional data (deaths in 17 European countries). Then, Eksler et al (2008) contributed to developing this approach by conducting a regional analysis of the indicator in 25 European countries.

It is necessary to stipulate a long-term objective of eliminating road deaths and serious injuries but also establishes a system approach to road safety, meaning that the design and function of the transport system are to be adapted to the conditions required to meet this goal. This has made attribution of responsibility for road safety to all those actors who influence the function of the transport system a key element of the policy, making this an interesting case for studies of road risk (Hysing, 2019).

2.2 The choice of aggregation level

The identification of spatial units often influences statistical results and conclusions. However, there has been little effort in the literature to identify the optimal level of aggregation for spatial analysis of traffic accidents, although reducing the geographical scale of analysis is an important tool to better visualize the road image of each region. In general, the use of large spatial units provides more reliable rates, but may mask some significant geographic variations (Deboosere and Gadeye, 2002). While the use of small spatial units tends to produce unreliable rates, but provides more accurate information. However, empirical analysis of spatial data is generally represented by two levels of aggregation: highly aggregated data that concern States or countries, and local data such as those on road sections (Lanzendorf and Busch-Geertsema, 2014). It is therefore remarkable that the identification of the level of intermediate aggregation for regional analysis is very rare in the literature. This may be justified by the availability of appropriate data or methods.

2.3 Bayesian models with spatial correlation

According to the literature, Bayesian models are considered one of the most relevant methods in the field of accident risk analysis. In this regard, Bayesian methods have been used by several researchers (Carlin and Louis, 2000; Cheng and Washington, 2005; Hauer, et al, 2002; Persaud, et al, 1999). In addition, they frequently apply spatial analysis. The Bayesian approach allows any form of coherent random effects or non-linear correlations between variables to be taken into account (Faber and Maes, 2005). In terms of regional analysis, these methods also simplify data smoothing in cases where the regions studied have some sparsely populated areas (Dean and MacNab, 2001; MacNab and Dean, 2002; Manton, et al., 1989). Consequently, Bayesian ecological modelling allows the projection of data over space, and consequently, the determination of accident risks by region.

2.4 The explanatory factor "population density"

In general, researchers assess road safety performance by analysing its evolution over time and feeding their work with comparative data from other countries. Similarly, for Lassarre and Thomas (2005) and Eksler et al (2008), population density is used as a spatial indicator explaining road risks between European regions. Population density takes into account many factors that are often not available at the regional level, such as road traffic, road network structure and urbanization. It can be assumed that densely populated regions have more modern and safer road networks and developed public transport options. This is because these centres of political and/or economic power require the response to increased demand for mobility by the population, and consequently the improvement of infrastructure (George and Verger, 2013). However, mortality is higher in rural areas than in urban areas. There are many reasons for this, including inadequate emergency services, speeding, drink-driving and a weak "enforcement" system (Clark and Cushing, 2004; Clark, 2003).

3. METHODOLOGY

3.1 Data

This analysis is based on the administrative division of the Tunisian territory. The data are analysed according to three geographical units with unequal areas and population sizes (districts, governorates and delegations), which follow an intermediate level of aggregation (regional level). The data used in this study come mainly from two sources. The first source is the NRSO database, which provides us with regional data on road deaths in 2014. The second source is the General Census of Population and Housing in Tunisia (RGPH) in 2014, which allows us to collect regional data on demographic and geographical characteristics such as the number of populations, population density, etc. The basic indicators of the aggregation units summarized in Table 1 show great heterogeneity in terms of area and population at all levels of aggregation. Although the administrative division of the Tunisian territory is based on population criteria, disparities may even exist between the demographic characteristics of several regional areas belonging to the same geographical unit.

Table 1. BASIC INDICATORS FOR GEOGRAPHICAL UNITS IN 2014

Aggregations level		**District**	**Governorate**	**Delegation**
Number		6	24	264
Area (Km²**)**	***Average***	25757.9	6439.5	585.4
	Minimum	11608.8	242.1	1.5
	Maximum	55222.3	38889	27380
Population (Thousands)	***Average***	1830	458	41.6
	Minimum	602	108	4
	Maximum	4177	1056	130
Road fatalities	***Average***	261	65	6
	Minimum	101	21	0
	Maximum	525	167	37

3.2 The choice of dependent and explanatory variables

Several dependent variables come from the road safety level measurement. The mortality rate is one of the most used variables in studies. In general, this variable is the number of road fatalities in region i (Y_i) for one year divided by the total number of inhabitants residing in the same region i (N_i) for the same year and noted :

$$T_{mi} = 1000\, Y_i / N_i \qquad (1)$$

Also, many explanatory variables are used to describe the relationship between dependent variables and the various road accidents factors. We have identified a set of general factors that may include many sub-factors that are not available at the regional level. For this analysis, the choice was based on population density as an explanatory variable since it can be conceived as a factor of exposure to mobility demand, demographic characteristics, urbanization, etc. The choice was made on the basis of the population density (Clark, 2003).

In order to examine the relationship between the explanatory factor and the dependent variable for each level of aggregation, a correlation analysis test between the two entities is used. To do this, we have applied the logarithmic transformations of the population density and the mortality rate to different geographical units. Indeed, we find that the Pearson product-moment correlation coefficients (r) are very significant for each geographical unit, since they prove the existence of a strong negative relation between the two variables. For the districts, the coefficient (r) shows a strong negative correlation (r = -0.91), a relatively strong negative correlation for the governorates (r = -0.43) and it is low for delegations (r = -0.26).

Furthermore, Fig. 1 and Fig. 2 show the distribution of delegations in terms of mortality rate (log TM) versus population density (log DP) for each governorate. Indeed, these figures present statistical evidence on the type of the relationship between the variables previously mentioned. Referring to Fig. 1, we can conclude that the relationship is well observed for 17 governorates. The correlation is presented by a negative monotonic curve, which means that the two variables vary in opposite directions. Indeed, the high values of the explanatory variable (population density) correspond to the low values of the dependent variable (mortality rate). In other words, the mortality rate in the governorates decreases as the population density increases.

Regarding the Fig. 2, we note the absence of the relationship between the population density and the mortality rate for the 7 governorates. This result can be explained by the existence of an ecological error. The lack of correlations for some governorates is mainly due to the difficulty of bringing together delegations that compose a single geographical unit, but have different road environments.

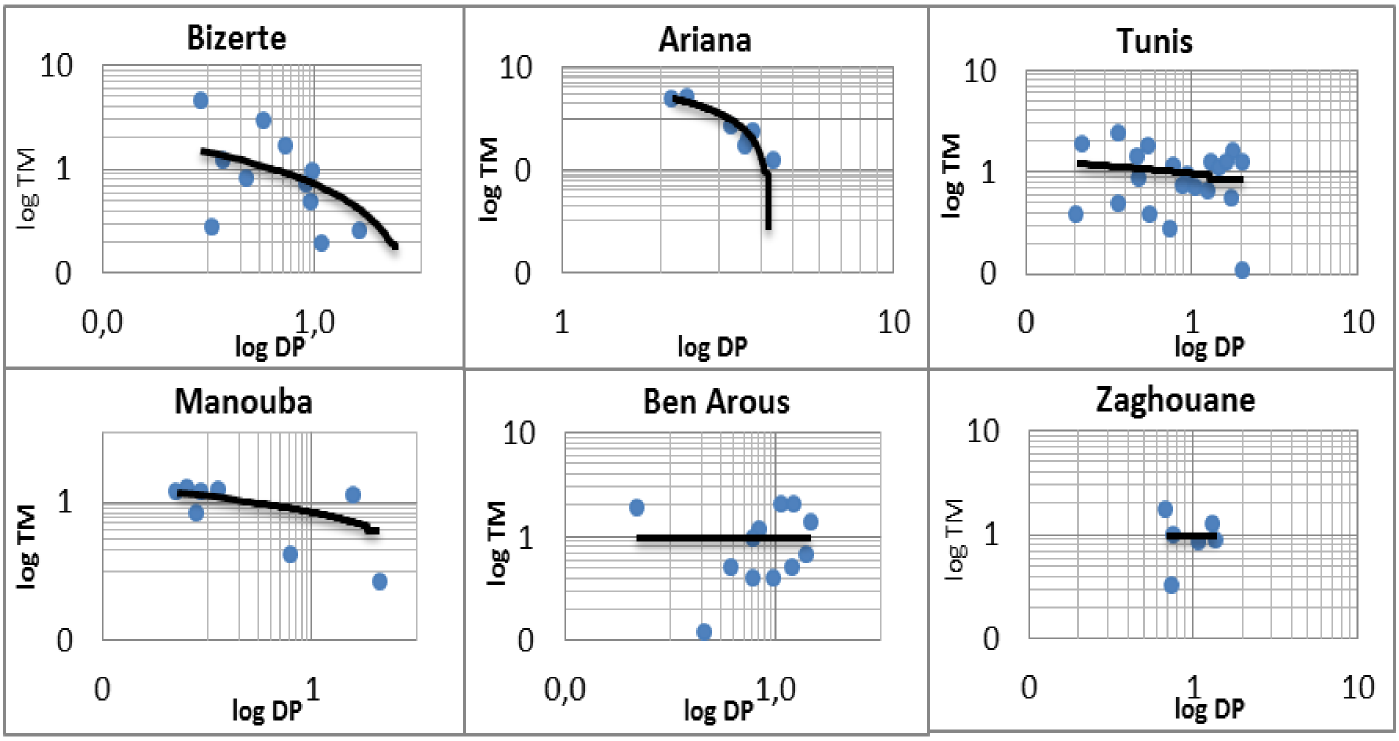

Fig. 1. The existing relationship between population density and mortality rate for the delegations of each governorate. (log scale)

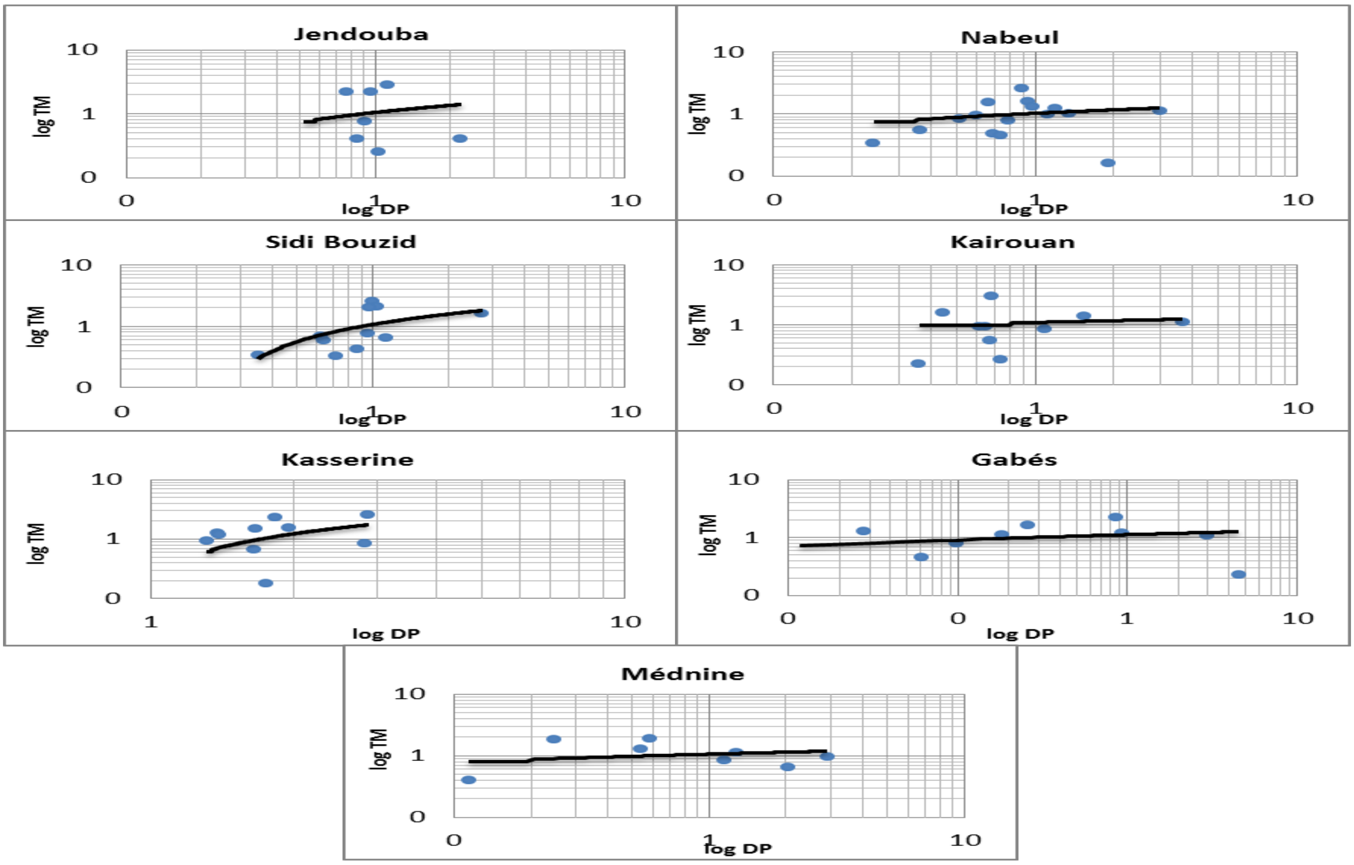

Fig. 2. The missing relationship between population density and mortality rate for the delegations of each governorate. (log scale)

3.3 The Bayesian ecological regression model

In our study, we propose the Bayesian ecological regression model in order to analyze the heterogeneity of road mortality in the different Tunisian regions. This model incorporates population density and geographical unit membership as factors. These two factors are considered as fixed effects for which regression coefficients are estimated; and a parameter that summarizes the random effects. Total road mortality can be easily modelled if we hypothesize that it follows a distribution of Poisson (Eksler, et al., 2008):

$$Y_i \sim \text{Poisson}\ (\lambda_i\ P_i) \qquad (2)$$

According to (2), the Poisson parameter λ_i and the term P_i show respectively the mortality rate and the population size per region *i*. This model can be extended to form a generalized mixed linear model that includes these fixed factors and a random effect within the mortality rate λ_i as follows :

$$Y_i \mid \nu \sim \text{Poisson}\ (\lambda^{\nu}_i\ ) \qquad (3)$$

According to (3), λ^{ν}_i represents the expectation of Y_i given all the random effects. In the analysis of mortality rates, the model is assumed to take the form :

$$\log\ (\lambda^{\nu}_i) = \log\ (P_i) + \beta_1 + \beta_2 \times (\log\ (DP_i)) + \nu_i \qquad (4)$$

According to (4), log (λ^{ν}_i) represents the expectation of Y_i conditioned on random spatial effects ν_i , log (P_i) is an offset population level intercept, the parameter β_1 is a fixed effect measuring the strength of the correlation between the geographical unit and mortality rate in region *i* (geographic unit affiliation), and β_2 is a fixed regression parameter for population density (DP_i). The random effect ν_i refers to all the ambiguities involved in the differential mortality rate for each region *i*, such as arising due to reporting error (inaccurate number of deaths or injuries due to the non-prosecution of victims within 30 days after the accident), missing covariates, over-dispersion or even genuine underlying differences in mortality rate. Then, the exponential of fixed and random effects exp ($\beta_1 + \beta_2 \times$ (Log (DP_i)) + ν_i) can offer a new significant parameter that represents the local area mortality ratio or the Bayesian relative risk, adjusted for geographic units and population density.

3.4 The parameters adjustment method

In this part, we propose the Monte Carlo method using Markov Chain (MCMC), which has a set of efficient statistical procedures for fitting models that are difficult to solve analytically. Indeed, MCMC makes it possible to carry out an estimation of the posterior distribution which cannot be done analytically for certain models. However, there are other approaches such as the grid search method and the Sample Importance Resample (SIR) method, that share a calculation problem when the data is rather informative. The most important part of the posterior probability is in a small part of the parametric space. In this case, most likelihood assessments have a negligible contribution to the total probability, so that the area of parametric space with the highest posterior probability cannot be sampled appropriately. This can lead to a misjudgment. In this way, we have used the MCMC method, which is the most efficient for us, in terms of calculation for problems with many parameters and a complex likelihood function. The only disadvantage of this approach is the impossibility of converging on the right solution, which requires us to carry out a convergent diagnosis. The model is subsequently adjusted using the OpenBUGS[2] because this software is particularly capable of adapting these spatial models. The Bayesian Inference Using Gibbs Sampling (BUGS) project focuses on flexible software for Bayesian analysis of complex statistical models using MCMC methods. OpenBUGS is a free software, providing a graphical interface to access the various modeling utilities. It is also available as a package in Stata and R. The Bayesian approach requires the use of some prior assumptions about the model to be made. The parameters β_1 and β_2 are assumed to follow respectively a uniform distribution (-2, 2) and (-2, 0). The precision (inverse value of variance) τ is assumed to follow a gamma distribution $\tau \sim (0.01, 0.01)$. To resolve the convergent parameters problems, we realize numerous iterations. After the first 20,000 iterations, all the model's parameters converge to the exact values of posterior distributions.

4. RESULTS AND ANALYSIS

4.1 Ranking geographical units by standardized mortality rate

In this part, we standardize the mortality rate by population and centralize it by 1 in order to well schematize the geographical unit's classification.

$$T_{mi}{}^* = T_{mi}\ /\ MT_m \qquad (5)$$

According to (5), we have divided the mortality rate of each region (T_{mi}) by mortality rates of the regions that belong to the same geographical unit (MT_m). The identification of the variation in spatial data is described by their average and standard deviation, while we have eliminated the variation in the average mortality rates. For Table 2, the standard deviation increases as the number of regions rises. The more the data are disaggregated into small spatial units, the greater the observed variations (this result confirms the importance of using regional analysis).

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[2] referring to Bayesian Updating by Gibbs Sampling

TABLE 2 : STANDARD DEVIATION OF MORTALITY RATE STANDARDIZED BY POPULATION FOR EACH GEOGRAPHICAL UNITS (AGGREGATION LEVEL)

Aggregation Level	Standard Deviation
District	0,154
Governorate	0,301
Delegation	0,856

However, the responsible intitutions in Tunisia often do not use a risk indicator to compare between the governorates. Hence the contribution of this study, which proposes a new classification based mainly on the standardized mortality rate by population size (risk indicators) Fig.3 schows the ranking of the 24 Tunisian governorates according to the standardized mortality rate. As a result, we can identify 3 groups :

- Two governorates (Bizerte and Ariana) with a very low road mortality rate. This comes back to their specificities in terms of traffic conditions. The Bizerte region is characterised by the absence or reduction of transit traffic due to its geographical location. As for the Ariana region, it is characterized by the importance of its residential housing.
- The governorates with a standardized mortality rate that varies around the mortality rate average of the geographical units.
- Three governorates (Zaghouan, Beja and Medenin) with a very high standardized mortality rate. This can be explained mainly by the geographical position of these governorates, which constitute bridges linking several governorates, and by their low population densities, which are 61.7, 81 and 52.2 inhabitants/km respectively.

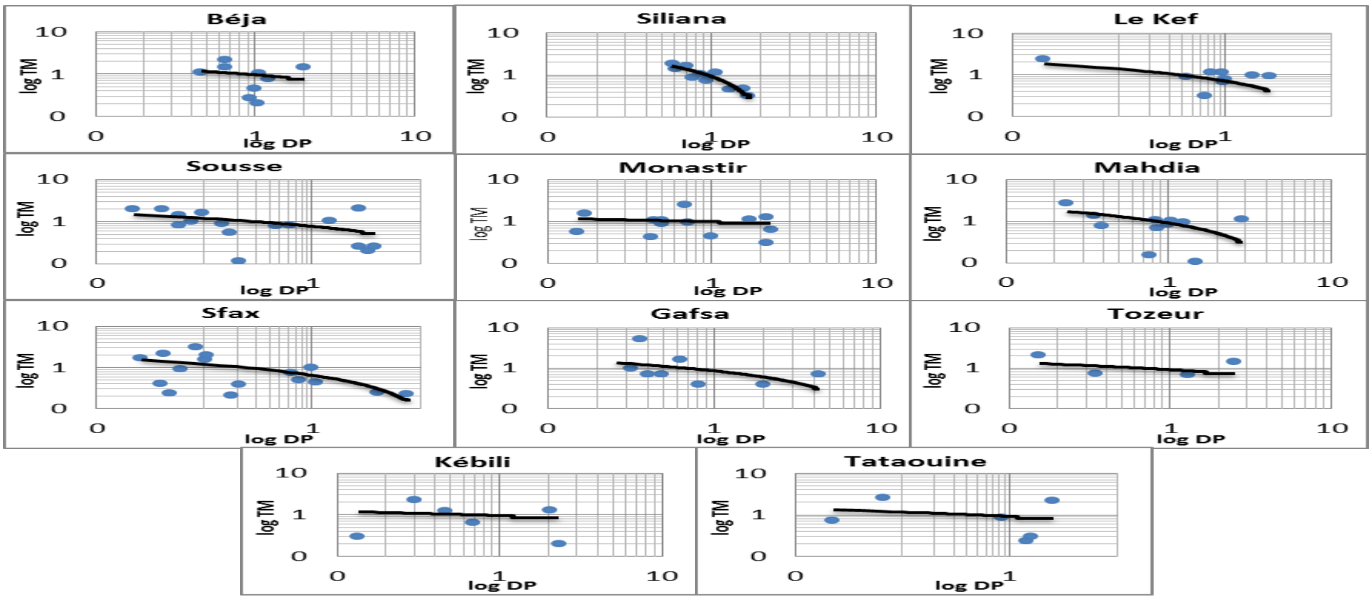

Fig. 3. Ranking of the 24 governorates according to mortality rate standardized by population (mean value for level aggregation)

4.2 *The effect of level aggregation affiliation and of population density*

After studying the classification of geographical units by normalized mortality rate, we consider treating, under the approach of the models presented above, the effect of spatial aggregation on the regression parameter of level aggregation effects. Regarding Table 3, the standard deviations of the regression parameter $\sigma(\beta_1)$ and the random effects parameter $\sigma(\nu)$ show that both standard deviations remain a simultaneous decrease.

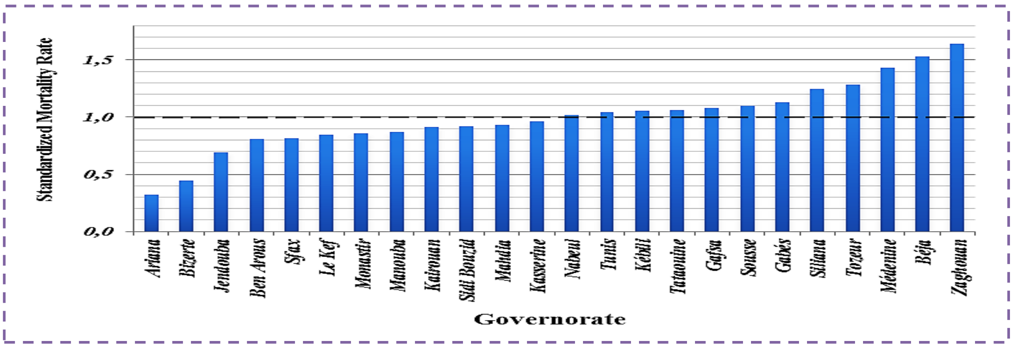

Table 3. THE STANDARD DEVIATIONS OF THE REGRESSION PARAMETER (B_1) AND THE RANDOM EFFECTS PARAMETER (ν) FOR EACH SPATIAL LEVEL AGGREGATION

Standard Deviation	**Districts**	**Governorates**	**Delegations**
$\sigma(\beta_1)$	0,675	0,162	0,012
$\sigma(\nu)$	0,415	0,334	0,235

These results show that it is possible to observe the same degree of heterogeneity in road mortality in all geographical units. We can therefore conclude from this analysis that national road safety interventions have a similar impact regardless of perceived regional differences at all levels of aggregation (traffic conditions, mobility demand, nature of infrastructure, etc.).

Using the Bayesian ecological regression model for each level of spatial aggregation allows to study the changes in model parameters in detail. The fixed regression parameter for population density on the occurrence of road mortalities β2 changes significantly at different levels of spatial aggregation. It went from (-0.254) for the districts and (-0.07) for the governorates to (-0.007) for the delegations. As a result, It can be deduced that 10% increase in population density at the district level leads to a 2.5% decrease in road mortality frequency and vice versa.

4.3 The Bayes relative risk mapping

The relative Bayes risk (the exponential of fixed and random effects) represents the road mortality rate standardized by population density and geographic affiliation. This is a parameter that can be mapped using QGIS (Quantum Geographic Information System). This geolocation work is a valuable tool as it allows quantitative and geographical data to be superimposed. It is useful for visualizing the road death toll in Tunisia and allows a detailed diagnosis that takes into account the intensity and characteristics of geolocated road accidents. The natural breaks classification method is used to make a choice of the class limits. This technique is also known as the Jenks' method which identifies breakpoints by searching for groupings and patterns inherent in the data.

Generally, the result given by the Bayesian approach can be visualized on maps that have a more heterogeneous structure. According to Fig.4, all the significant variations (that we have distinguished in Fig.3 of Ranking of the 24 governorates) remain clearly visible on the map (e.g. Zaghouan which has a very high mortality rate and Bizerte which has a very low mortality rate). Moreover, Fig.5 shows that the heterogeneity in the Bayes relative risk for the delegations is also visible in governorates where the mortality rates have a rather homogenous pattern (for example Béja, Siliana and Kef). Furthermore, the highest variance in Bayes relative risk between delegations belonging to the same governorate is apparent in Gabes and Tataouine. The importance of using a regional analysis to study the hidden statistical variations can intervene for the identification of new fragmentations in the governorates themselves. As a result, there is a North/South and interior/Coastal heterogeneity of Bayes relative risk in some governorates (e.g. Sousse and Mahdia). This discrepancy can be explained by several factors such as economic inequalities between the northern and southern delegations of some governorates or demographic, geographical and climatic conditions. For example, the delegations in Sousse have significant differences in terms of land use (administrative, leisure, etc.), mobility demand and infrastructure quality, which require the adaptation of the measures to be taken in the field of road safety At different levels of aggregation, a hidden structure of road mortality risk appears when analysing trends in Bayes' relative risk. It can be used to provide a clear vision of the road safety situation in Tunisia.

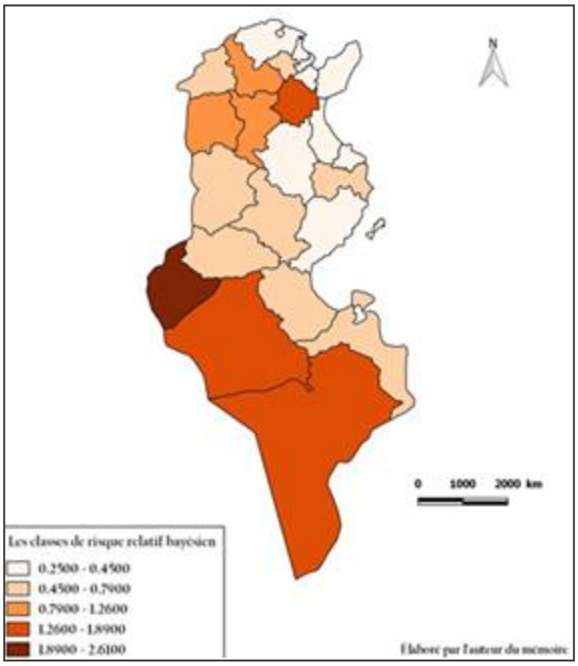

Fig. 4. Representation of Bayesian relative risk classes in Tunisia in 2014: governorate aggregation level.

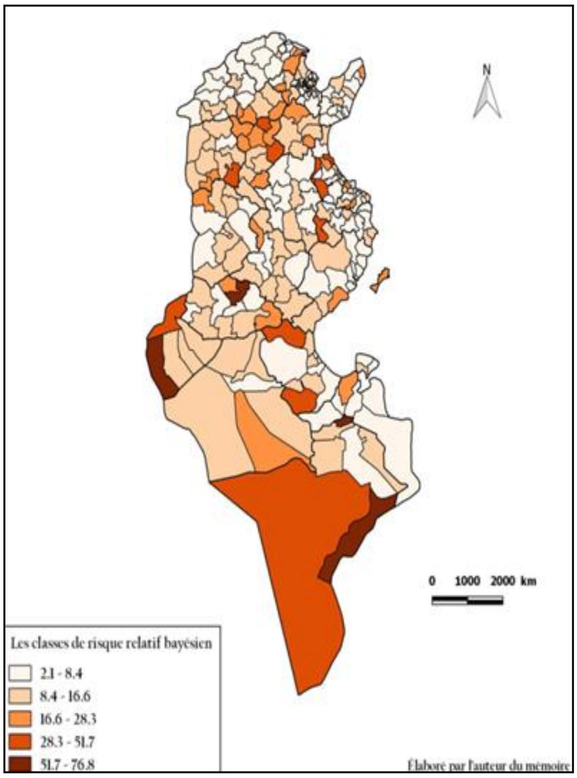

Fig. 5. Representation of Bayesian relative risk classes in Tunisia in 2014: delegation aggregation level.

5. CONCLUSIONS

Regional analysis is considered to be one of the spatial analyses that can provide information on variations in the level of road safety in countries. It allows access to and use of regional data. To succeed in this analysis, differences in area and population between regions at the same unique level of spatial aggregation must be taken into account. In order to overcome the difficulty due to the lack of available data, we have limited ourselves in this analysis to the influence of population density (as a synthetic explanatory factor) on the observed level of road mortality in Tunisia. Indeed, variations in road mortality at delegation level appear to be very high compared to variations at governorate level, mainly due to a wide range of additional explanatory factors. These factors, which are mainly economic inequalities and geographical, demographic and climatic conditions, contribute to justify the heterogeneity of road mortality between regions belonging to the same spatial unit. On the other hand, this study has shown that national road safety provisions have a similar weight to regional differences at all levels of aggregation, such as traffic conditions, mobility demand, nature of infrastructure etc. whereas in reality each region has different characteristics.

Investigating the effects of population density and geographic unit affiliation on the road mortality rates leads to several results such as a new ranking of governorates. The governorates of Zaghouan, Beja and Medenine are the worst in terms of mortality rate. This analysis shows that the variation in road mortality risk is higher at the level of delegations than at the level of districts and governorates. This proves the existence of other explanatory factors observed in the regions. It is Neverthelessdifficult to explain these variations clearly. The contribution of this study is to take into consideration the impact of population density on road mortality to the extent that demographic data contribute to providing information on traffic conditions in any given territory.On the basis of this result, it would be important to highlight the effectiveness of certain road safety actions that target limiting traffic speeds in urban areas (30 km/h zones), improving public transport to minimise private car use, strengthening road rescue and building safe infrastructure.With regard to road mortality, the fight against fatal accidents should take into account the increase in population density. According to this study, a 10% increase in population density at the district level could lead to a 2.5% reduction in road deaths. The mapping of the relative risk of the Bayes allows the coupling of alphanumeric criteria and the geolocation of fatal accidents. Visualization of the road image of each region in terms of mortality could guide road safety action plans. It would help decision-makers at all levels to better understand road safety, identify territorialized issues and make targeted decisions. It is a decision-making tool that can be effective. Mapping could also be used to highlight black dots related to road mortality. Pointing this data on maps would help to prioritize the corrective actions to be taken. Rapid reactions would be required in regions with high mortality rates. It would be advisable for the Tunisian authorities to take action on speed control by radar, road and land use planning, urbanization and demographic movement management, road user awareness, etc.

This study is exploratory in nature. It proposes a new contribution in terms of analysis of road accidents in Tunisia. Nevertheless, we are aware of the methodological limitations of this study such as the use of the total number of inhabitants in the mortality rate, mobility demand or traffic.Through to the use of Bayesian modeling, this study presents a mix of random and fixed effects, which schows the advantage of this method compared to the general linear models commonly used. This study also shows that the analysis models can provide a clear overview of the road safety situation and can be a robust tool for decision makers to develop a national policy that must reflect a good gouvernance. This study also shows that analytical models can provide a clear overview of the road safety situation and a solid tool for decision-makers to develop a national policy that should reflect good governance. The results obtained reflect the characteristics of the Tunisian context and can serve as a testimony of experience. Public policies should be adapted to the specificities of each country or region. The introduction of new variables into the analysis enriches the diagnosis and provides a better understanding of the problem. From a spatial planning perspective, this study lays the cornerstone of good practice in the spatial analysis of road accident data in Tunisia, which is useful for the development of an appropriate and well-defined public policy. The results of the study are in agreement with those of Ouni and Balloumi (2019), who treated the Tunisian context according to a specific spatio-temporal approach : three regions (North-West, Central-East and Central-West) and for three periods (2002-2005, 2006-2009 and 2010-2013).

In conclusion, this study is part of a process of understanding the dysfunctions that contribute to worsening the toll of road insecurity in Tunisia. This work stems from a recognition of the socio-economic burdens borne by the nation and presenting a challenge to be met. Moreover, this reflection, which we have developed in this article, leads to ideas and perspectives that can inspire dynamic researchers in several disciplines. This effort could be improved with further investigation. Indeed, relying on more detailed and better structured databases could provide a more in-depth analysis and better identify the factors that explain the occurrence of accidents. It would therefore be interesting for data analysis and computer experts to enrich this spatial analysis with other explanatory variables. This research initiative could also involve geographers and urban planners in a more detailed analysis of the link between spatial planning, in its various dimensions, and road safety in Tunisia. Studies have shown that action to improve road safety is not only the concern of road engineers, but also of planners and urban planners (Fleury and Mandigon, 2005). This research could also mobilize researchers in management and economic sciences to address the importance of involving road safety in decision-making and public policy development.

The authorities should also pay particular attention to infrastructure management and design. In particular, the needs of vulnerable road users (pedestrians, cyclists and motorcyclists) should be taken into account in road design in view of their high involvement in road mortality (approximately 35% in 2018 in Tunisia, according to NRSO). Investment should also be made in specific technologies for monitoring and equipping road infrastructure, while strengthening the enforcement system (Carnis et al., 2019). The results of these studies should be shared with local, regional and national decision-makers. Good coordination between the different actors is necessary to carry out synchronized actions. Finally, we emphasize the cross-disciplinary and multidisciplinary characteristics of road safety. This is a complex and multi-sectoral area. It draws on several complementary areas of expertise to provide a better analysis of the situation and propose useful operational solutions for local, regional and national decision-makers.

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