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Use of Historical Road Incident Data for the Assessment of Road Redesign Potential

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Abstract: Drivers' safety and overall road functionality are key triggers for deciding on road interventions. Because of the socioeconomical implications of traffic incidents, either fatal or no, continuous research has been dedicated over the previous decades on the assessment of factors contributing to crash potential. Apart from the behavioral aspects of driving, which are commonly studied through simulation and advanced modelling techniques, the road infrastructure status is of equal or even higher significance. In this study, an approach is presented to discuss the road redesign potentials based on the evaluation of network-level historical incident records from road crashes in Greece. Based on total and fatal crash records, the following infrastructure-related aspects were assessed as critical for the discussion of the road redesign potential needs: the status of road's surface (i.e., dry, wet, etc.), the issue of improving driving conditions near at-grade intersections, the presence and suitability of signage and/or lighting, and the consideration of particular geometric design features. Overall, it is deemed that intervention actions for at least one of these pillars should aim at enhancing the safety and functionality of roadways.

Keywords: crash records; road surface status; road redesign; signage; lighting; drivers' safety; road functionality

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1. Introduction

1.1. Background on the Social and Enviromental Implications of Roadways

Prior to the construction of safe roads, these are geometrically designed in a way that comprises a three-dimensional layout that balances out three distinct elements, i.e., the horizontal alignment, the vertical alignment, and the cross-sectional profile. Selecting appropriate design values for tangents, curve radii, longitudinal grades, sight distances, lane widths, transverse slope, etc., guarantees adequate traffic flow at typical operating speeds along with functionality, safety, and an environmental-aesthetic adaptability of roads [1,2].

In the meantime, road collisions continue to be a huge global problem with great economic and social implications, despite tremendous efforts and pertinent advances in improving road safety. The World Health Organization's most recent assessment of global road safety states that traffic crashes claim the lives of 1.35 million drivers worldwide each year, ranking them as the eighth most common cause of death for people of all ages [3]. Significant disparities exist in the performance of road safety throughout the various world regions, with Europe recording the lowest numbers of deaths per population [3]. There are notable variations among the regions of a nation as well, which may be related to a number of socioeconomic issues [4].

Enhancing the safety of the European road network is a priority for the European Commission (EC). In order to achieve this goal, the EC approved some years ago the Road Safety Program, which sought to reduce traffic fatalities by half by 2020 compared to 2010. Nevertheless, as the recorded fatality reduction was equivalent to 37%, this aggregate aim

was not fulfilled everywhere [5]. Greece was the only member of the European Union (EU) to meet this goal, with a performance of −54%. In addition to the fact that Greece experienced a major economic recession, there could be one major reason for the notable decline in road fatalities in the country over the past ten years. This relates to the fact that the main road network was significantly improved, with 2200 km of motorways in 2018 compared to 750 km in 2007 [5]. Greece, however, was placed 23rd out of 27 EU nations in 2023 for road fatalities per million people, which is far higher than the average for the EU, which is 46 per million people [6]. As a result, it appears that sustained and coordinated efforts are continuously needed to solve this significant issue of traffic accidents.

From a different perspective, roadways encompass environmental and sustainability-related components. When vehicles move on a roadway, they consume fuel and, thus, emit pollutants [7]. The contribution of the transportation sector, and in particular road transportation activities, to environmental pollution is well-known so far. Based on data from the International Energy Agency, the global transport sector produced 8 million tons of CO_2 emissions in 2019, or roughly 1/4 (24.2%) of all CO_2 emissions worldwide. Of these, 6.5 billion tons were produced by the road transportation sector, making up 81% of the transportation sector as a whole [8]. Hence, it is a big challenge for road engineers and vehicle industries to seek for countermeasures to meet sustainability principles in roadways, like eco-friendlier vehicle technologies [9,10] and peculiar characteristics of road design and/or pavement surface condition that could ensure less fuel consumption [7,11]. In parallel to the environmental component of vehicle movement on safely designed roadways, speed choice conforming to speed limits is one of the core pillars to meet sustainability principles in traffic safety, thereby preventing road deaths, serious injuries, and permanent injury by systematically reducing the underlying risks of the entire traffic system.

1.2. Background on the Intervention Potential

While there is enough margin for improvements in the national and international road network, it is a matter of fact that modern road planning, construction, and maintenance repeatedly call for the wise and efficient use of scarce financial resources. In the meantime, the majority of the road network and corridors are completed or are under construction at both the national and international level [12]. In other words, planning for completely new roadway paths might be almost absent, especially in the developed countries. As such, it can be confidently stated that during the preceding decades, the concerns of roadway engineers have been directed toward the upkeep and restoration of the existing road network by slight interventions in the geometric design and by more frequent interventions because of poor pavement condition [13]. The main reason for that is again the budgetary constraints of road entities.

On these grounds, effective road maintenance guidelines are now regarded as being just as significant as sound initial construction and building techniques. A quite frequent and first-decision action when planning interventions in a roadway is to focus on the restoration of road surface condition. Of course, a prerequisite is that the pavement's structural and mechanical behavior is adequate [14–16]. Moreover, this is aligned with the concept of long-life, or perpetual, pavements, where structural soundness is guaranteed in the long term and only surface interventions to improve road serviceability take place [17]. Among the road surface characteristics, tire–road friction is drastically related to safe driving conditions and can be a contributing factor to road incidents [18]. Indeed, nearly 120,000 individuals lost their lives on U.S. roads between 2010 and 2013 [19]. Even in the event of non-fatal incidents, the economic implications are unquestionably dominant in addition to the potential for societal disturbance due to unfriendly and hazardous road infrastructures [20].

Other minor treatments that can be chosen before deciding for redesign interventions include improvements in signage, road markings, and/or lighting conditions especially during night hours on roadways with high incident risk potential [21]. The presence of road safety barriers is another critical safety factor of a hazardous roadway section. If none

of the above can contribute to a safer and more sustainable driving mode, then modification or improvement of road design aspects during safety interventions in existing parts of the road network could be opted for. Of course, potential restraints because of the terrain configuration and the available space must be considered, which is usually a matter of concern, especially in urban or suburban areas [7].

Towards better addressing the needs for potential road redesign, the necessity of using various forms of qualitative assessments and analysis is emphasized in the EU Directive on Safety Management of Road Infrastructures [22], including safety audits for the improvement of existing roads and inspections of existing roads to identify safety issues in several road design aspects, and safety audits to suggest intervention improvements [23].

Key common triggers for interventions on the roadways are road safety and the provided functionality for drivers. Because of the socioeconomical implications of traffic incidents, either fatal or no, continuous research has been dedicated over the previous decades on the assessment of records of traffic volumes and crash rates [24]. Driving behavior under various sensitivity analyses of road design parameters, traffic and weather scenarios has been extensively investigated through the use of a driving simulator that can mimic real traffic conditions, in order to retrofit road design procedures [25]. Although the latter seems promising, its use needs caution because of the deviations between the predicted and the observed driving performance [26]. Further to this, the behavioral aspects of driving are commonly studied through simulation and advanced modelling techniques, whereas infrastructure status is of equal or even higher significance.

1.3. Objective

Thus, in this study an approach is presented to discuss road redesign potential based on the evaluation of network-level historical incident records from road crashes in the Greek road network for a seven-year period, i.e., 2016–2022. Publicly available data from the website of the Hellenic Statistical Authority reflecting different aspects of road infrastructure status [27] were analyzed to identify major contributing factors that can be thereafter assessed in order to strategically draw potential intervention plans. Besides the behavioral component of road safety, which is extensively addressed in the literature, the discussion provided in this study has to do with infrastructure-related components that are of equal, if not higher, significance, and are almost overlooked or sparsely investigated in the international literature.

The rest of the paper is organized as follows: Section 2 provides remarks and findings about common existing practices during road intervention planning. Section 3 includes the processing of the available data from the incident records together with supportive discussion points. Section 4 provides the concluding remarks of the current study.

2. Aspects to Consider for Driving Conditions Improvement and/or Road Redesign

2.1. Pavement Surface Characteristics

The condition of a pavement's surface directly affects driving safety. Pavement friction is the most known pavement characteristic that guarantees efficient vehicle maneuvering when brakes are applied, a quite necessary action especially under wet-weather conditions. The water film on the pavement surface reduces the contact area between the tire and the road surface, thereby increasing the potential for skidding events or even hydroplaning [28,29].

The behavioral attributes of skid resistance are well reported elsewhere [30,31]. Herein, for the sake of completeness, it is worth recalling its seasonal variation performance. According to Figure 1, after a prolonged dry period without rainfall, dust and other contaminants are expected to be present on the pavement's surface. Thus, skid resistance tends to be reduced as a result of the combined effect of "pollutants" and extended dry spells. Practically, a fine layer of contamination is built up on road surfaces, which can be particularly intense on heavily trafficked highways, because of the repeated tire–road wear

process [31]. This layer can consist of particles of rubber, bitumen, road material, dust, and other debris that are all mixed together to form a kind of pollution.

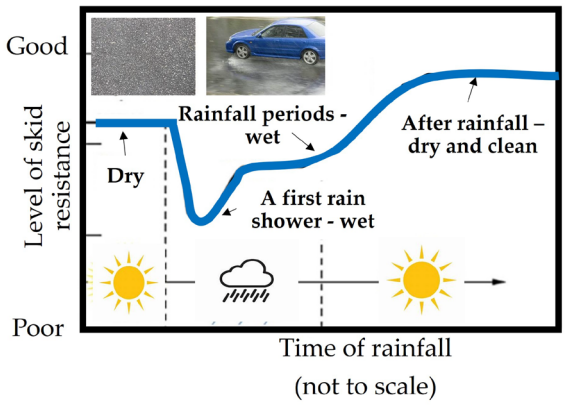

Figure 1. Illustration of friction level variation because of weather changes (adapted from [31,32]).

Rainfall is normally expected to wash the contaminants away. But after a prolonged dry period, the previously mentioned fine layer is additionally mixed with a small amount of water from the first and short rain shower events and the result is an extremely slippery road surface (also called the "summer ice" phenomenon), which is usually perceived by experienced drivers as a risky condition. Once rainfall persists for a long period, the "washing and cleaning" phenomenon takes place and as a result, skid resistance appears increased after a long period of rainfall with usually higher levels compared to the available friction in dry periods (right part of Figure 1) [31,32]. This is why many highway entities may tend to measure skid resistance twice per year; once at drought periods and once after rainfall. It is noted that there are multiple methods for measuring skid resistance, like the static methods (e.g., British Pendulum Number), and continuous methods, like locked-wheel or fixed-slip systems [32]. A common standard for friction measurements is ASTM E2340.

There is much documentation supporting the liaison between road incidents on wet surfaces and the level of provided skid resistance. Indeed, improved pavement friction has the potential to prevent or reduce around 70% of wet pavement crashes, according to research undertaken by the Federal Highway Administration (FHWA) and the National Transportation Safety Board [33]. Using a before-and-after analysis, Lyon et al. [34] assessed the safety impact of several pavement surface modifications in California, North Carolina, Pennsylvania, and Minnesota. The interventions appear to have reduced wet-road collisions in a statistically significant way, based on the combined results for all treatment types. From a different research perspective, Geedipally et al. [35] characterized the link between crash frequency and traffic, geometry, and pavement characteristics for horizontal curves in a southern state of the United States and created safety performance functions. It was discovered that the skid number had a considerable impact on all incidents, with rainy weather run-off-road crashes exhibiting the highest safety benefit.

Lyon et al. [36] recently assessed the safety impact of High Friction Surface Treatments (HFSTs) in various U.S. States. A specialized pavement treatment called HFST is a thin layer applied on the pavement surface to improve or restore friction, consisting of high-quality materials. Local small-scale treatments of curves, ramps, intersections, and steep grades—where the need for friction is greater than what can be met by traditional paving materials—are frequently carried out with it. The results demonstrated the contribution to lane-keeping driving performance when cars navigated curves as well as the remarkable statistically significant crash reductions at curve sites. As such, skid-resistant pavements have been shown to be an effective strategy to target lowering run-off-the-road collisions [37].

Irregularities in the road surface that could lead to a driver losing control of their vehicle are another significant factor that could potentially be dangerous for moving

vehicles [38]. Unevenness (i.e., irregularities with wave-length between 50 m and 0.5 m) or roughness (Figure 2) is the profile of the road surface that impacts vehicle dynamics and water drainage. It is quantified using the International Roughness Index (IRI), expressed in m/km and calculated using a road profiler with a quarter-car math model at a standard speed of 80 km/h [39]. Because of the bilateral relationship of road distresses and roughness, already acknowledged in the international literature [40,41], rough surfaces can have the tendency to worsen pavement fatigue status, impose surface deformations, and raise vertical stresses in the pavement [40]. This could result in excessive surface distress, so that a driver may lose directional stability and increase stopping distances [37].

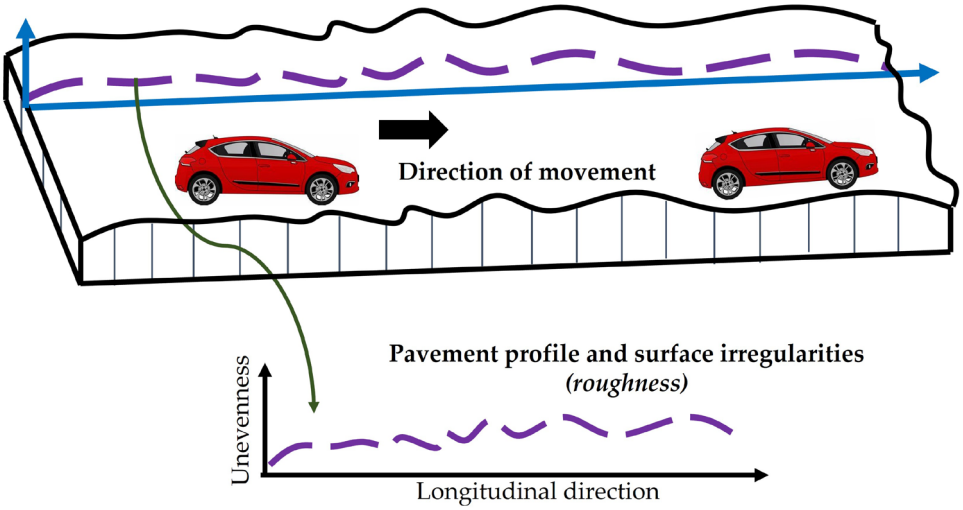

Figure 2. Illustration of a pavement surface with roughness issues (adapted from [39]).

The IRI is frequently used as the foundation for decisions on pavement maintenance because it is regularly gathered by numerous highway authorities across the globe and has been shown to accurately reflect the sense of road quality held by users. Indeed, Chan et al. [42] used long-term performance data from Tennessee to study the impact of pavement conditions (such as the International Roughness Index (IRI) and other indices) on collisions. They discovered a positive impact of the IRI on collisions, demonstrating that more frequent crashes are linked to poor pavement conditions. Nemtsov et al. [43] discovered most recently that there is a statistically significant correlation between an increase in IRI and a rise in crashes along two-lane rural highways.

Nevertheless, the surface characteristic that is most often used to trigger maintenance actions in favor of safe driving is skid resistance. In the case of pavement resurfacing, there can be indirect benefits, even short-term, in terms of restoring the ride quality as well.

2.2. Road Geometry

Once surface interventions to restore the pavement condition status seem to be insufficient, then one should more carefully consider the road design elements and evaluate the safety efficiency of the existing road network. Indeed, numerous studies have demonstrated how geometric design significantly affects traffic safety. AASHTO 2010's Highway Safety Manual (HSM) uses a number of crash modification factors (CMFs) to measure how changes in geometric design parameters from baseline conditions affect crash frequency [37]. The most commonly used geometric design features that are routinely investigated include lane width, shoulder width and type, horizontal curve superelevation, curve radius and length, existence of spiral transitions, and vertical grade [37].

It is a commonly accepted fact that safety effects on driving performance rarely depend solely on a single design factor. Researchers suggest that the impact of geometric design is multi-parametric and safe driving is greatly influenced by the overall highway alignment and the location of any geometric element in relation to the overall alignment and the

distance from the other geometric elements [44,45]. In the same context, Cafiso et al. [37] stated that a highway design that guarantees that subsequent elements are coordinated in a way that produces harmonious and homogeneous driver performance along the road is regarded as consistent and safe.

This justifies why it is quite impossible to improve safety conditions by marginal interventions in the road geometry, which are indeed costly and thus undesirable. Further to that, safety interventions at existing road sections are usually restrained because of potential constraints resulting from the layout of the terrain configuration and the available space [7], especially in urban or suburban areas, or in mountainous areas with sharp relief and increased height deviations that could require much more expensive technical works.

However, reality may usually contradict safety design principles. If the horizontal and vertical alignment of a roadway deviate from the safety criteria of road design, then sharp speed changes could be anticipated, something that can increase the likelihood of crashes. The directional changes in a horizontal alignment should be smooth, so that a driver can be alerted and increase his/her degree of attention and expectations about the future alignment of the road [44,46]. As such, a driver can properly adjust the vehicle speed. For instance, on a relatively straight road, a sharp curve is much more dangerous than one on a winding route because the driver might not anticipate it and thus needs more time to adjust the vehicle speed [47]. Moreover, it is not so unusual to observe more crashes on straight roads of high length [48,49], because of the increased speeds, something that can be magnified once the pavement is distressed enough (as explained earlier), and/or warning signage is rather absent.

Finally, the impact of visibility and sight distance is another crucial parameter of road design, as crash sensitivity for a given roadway section with erroneous design elements might be more intense and detrimental at night, thereby requiring additional countermeasures (e.g., lighting, signage). A combination of various design elements that seems to be functional for driving in daytime may not maintain this functionality during nighttime [50]. The role of lighting and signage is further explained in Section 2.4.

2.3. Intersections Versus Roundabouts

A roadway intersection is the area where two or more roads join or cross at-grade. One of the most dangerous places in the road transportation network is an intersection, where there is an increased likelihood of fatalities and severe injuries [51]. In both developing and developed nations, intersection-related crashes make up roughly 20–45% of all recorded crashes [52–54]. There are many different and complex circumstances that lead to crashes involving intersections. In most cases, drivers pay little attention to the complex environment of an intersection and may be prone to illegal maneuvering because of misconception and erroneous understanding of the possible driving directions [55]. Crash types, as well as their frequency and severity, are influenced by a variety of factors, including intersection kinds, vehicle control, and road geometry [56]. For instance, there are up to four times as many crashes at four-legged junctions than at simple T-intersections. Rear-end collision rates are higher at signalized intersections than at stop-controlled intersections [55]. However, compared to signal-controlled crossings, stop-controlled intersections see a higher number of angle crashes.

An innovative solution to cope with the increased incidents at intersections is to transform them into roundabouts. This action has shown that a sufficient degree of road safety and traffic capacity can be achieved [57]. Drivers need to slow down as they approach a roundabout in order to navigate it easily and exit it without being involved in an incident. Without traffic signals, traffic delays are therefore streamlined or even reduced. As a matter of fact, studies have shown that converting a signalized intersection into a roundabout reduces traffic delays by 89% and complete vehicle stops by 56% [58]. Roundabouts also have a special opportunity to raise drivers' safety. The explanation is straightforward: once the emphasis is on urban crossings, conflict points are drastically reduced (Figure 3), for both cars and pedestrians, in comparison to conventional intersections. The same does also

apply for roundabouts on rural roadways. Drivers are compelled to slow down, which makes it much easier to manage their risk of becoming involved in an accident with a pedestrian or another car [59].

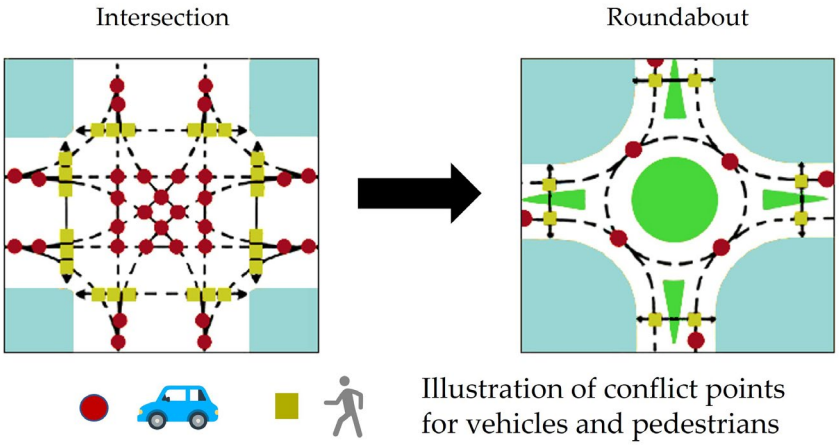

Figure 3. Comparison of the number of conflict points at intersections and roundabouts, including cross conflicts, merge conflicts, diverge conflicts, and pedestrian cross-walks.

Of course, the selection of an optimal type of roundabout (e.g., mini-roundabout, single-lane or double-lane roundabouts, etc.) with proper values for its geometric elements aims at reaching a balance between drivers' safety and traffic capacity. The drivers' perception of danger, which is influenced by their driving performance and experience, is undoubtedly influenced by geometric design components [60]. In order to ensure a smoother transition pattern at this type of cyclic intersection, vehicles should typically yield to the oncoming traffic rather than being forced to a complete stop at roundabout entry positions [61]. Because of the reduced vehicle speeds, Burdett et al. [62] found a 38% reduction in fatal injuries and severe collisions at roundabouts. Within the same framework, De Brabander et al. [63] found that the average rate of reduction for the total number of injury accidents at roundabouts was 38% for serious injury accidents.

However, it is still unclear how roundabouts affect the quantity of crashes that result in no injuries [64]. Polders et al. [65] claim that accidents still happen even with roundabouts' contribution to traffic safety. From a geometrical perspective, the number of the available lanes of a roundabout is critical. Overall, the likelihood of a light, non-injury crash increases with the number of lanes [57]. Indeed, Johnson [66] has recently noted a considerable rise in property-damage-only crashes at multi-lane roundabouts.

Nevertheless, the goal of interventions at intersections is to make the road infrastructure better and easily understandable for drivers with emphasis on vulnerable road users. Moreover, a rational and sustainable vision for safer roads comprises little or no fatal incidents, or the ambitious goal of "zero deaths" along roads [67,68]. Non-injuries crashes seem affordable, as it is impossible or at least unrealistic to fully eliminate them based on the randomness of human driving behavior even under ideal infrastructure conditions.

2.4. Additional Road Equipment

Even when a road's geometric design meets all safety criteria, there are still some actions needed to guarantee safe driving conditions. These include proper equipment to account for: (a) comprehensive signage and road markings, (b) adequate lighting, and (c) necessary road safety barriers in critical areas.

According to Cho et al. [69], there is no doubt that elements connected to the road environment, such as missing road markings, broken signs or traffic lights, and inadequate lighting, can have a direct impact on traffic incidents and/or fatal accidents. In summary, traffic safety signs alert drivers to possible dangers such as sharp curves, junctions, and construction zones and help them become gradually adaptable to the road environment.

They also offer guidance on how to handle these circumstances through safe navigation. In other words, drivers can become capable of higher cognitive activity once proper signs and markings are present [21]. Rightfully, road signs continue to be an essential public tool to ensure driving safety [70,71]. The likelihood and frequency of traffic accidents are decreased when traffic signs are appropriately obeyed. The kind and placement of the sign as well as the behavioral actions of drivers influence how much road signs reduce the frequency of traffic accidents. Important elements include traffic law enforcement, driver education, and safe road and highway design [72].

In the same context, road safety is greatly enhanced by clear and well-maintained road markings. Visibility is aided by the difference between the road surface and the road markings, particularly at night or in adverse weather. Numerous studies demonstrate a relationship between road markings and the lateral position of the vehicle within the lanes [73,74]. In particular, when the width of the road markings increases, drivers shift their vehicle's lateral position and bring it closer to the side of the road, lowering the possibility of a head-on collision [73,74]. The application of vibration markings, road curve signs, transverse warning markings, and markers result in a notable decrease in the incidence of centerline crossings.

Road illumination at night does, in fact, contribute significantly to traffic safety too. According to research by the International Commission on Illumination, road lighting decreased nighttime accidents in 15 different nations by 13–75% [75]. Road lighting in Belgium, Britain, and Sweden decreased the number of crashes that occurred at night by 23% [76]. As a result, assessing the quality of road lighting is important to increase urban traffic safety and the quality of the road lighting at night [77].

Of course, maintaining adequate lighting everywhere at night is impossible as this is translated into environmental costs. This is why intelligent street lighting has appeared as an alternative sustainable option, so that efficient and safe driving at night is no longer compromised. With a privileged domain of implementation in cities, smart lighting technologies, like the one illustrated in Figure 4, include motion detectors to activate illumination only when necessary. This can contribute towards the minimization of road crashes because of nighttime limited road visibility by simultaneously ensuring road functionality and energy efficiency.

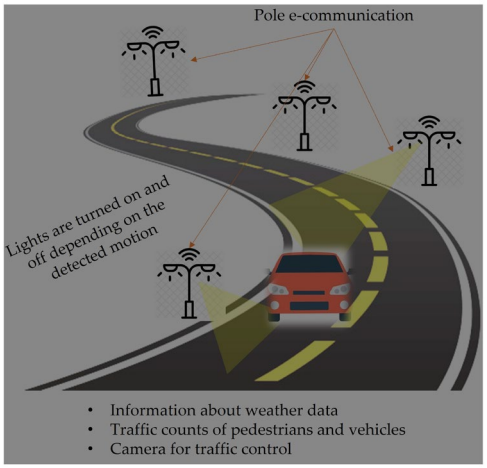

Figure 4. Conceptualization of a smart illumination system of roadways at nighttime.

Finally, standard safety measures, which are often implemented in the curves, are road safety barriers. Road safety barriers are part of the road restraint systems (RRSs) intended to prevent the vehicle from leaving the roadway [78,79]. The main contribution of a safety barrier is that when the driver loses control of the vehicle and leaves the roadway, the barrier can save his life by stopping the vehicle or redirecting it back to the road. It is

self-proved that their presence in a roadway environment is very important for the purpose of safe driving.

2.5. Importance of Accessing and Managing Data

If most of the above conditions were met, the infrastructure condition would be ideal, functional, environmentally aesthetic, and most importantly fully-understandable by drivers, resulting in a safe and sustainable driving performance. In many aspects of road safety, including infrastructure management, crash data are essential because they form the basis for risk assessment and the application of efficient safety measures. The availability and dependability of crash data, however, frequently present serious difficulties. Hence, ensuring road crash inventory data might be a challenge for those wishing to invest in reliable road safety research. A typical procedure of how data should be handled is given in Figure 5.

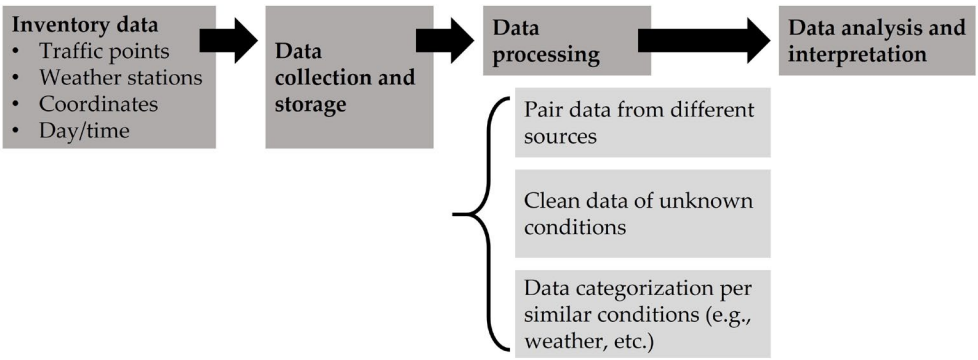

Figure 5. Conceptualization of effective road crash data management.

Of course, it is critical to look beyond obvious causation variables when studying crash data, since crashes can arise from a confluence of contributing events (e.g., traffic conflict points, weather status, poor pavement condition, bad road design, etc.). Again, multiple sources of data might be needed that could play a crucial role in the assessment of investments, especially in situations where funds are limited. To this end, it is crucial to show the efficacy of road safety initiatives in order to allocate scarce funds effectively and to identify and mitigate any potential increases in crash risk. Preserving the integrity of data is significant in order to avoid misreading or underestimating the number of casualties, which could jeopardize attempts to address road safety as a pressing public health issue [80].

Nowadays, with several advancements in data collecting techniques, the efficiency and accuracy of data analysis is much more improved, thereby yielding reliable results. Errors can be minimized and data gathering and interpretation procedures can be more easily homogenized. Rational and standardized data processing can definitively increase the usefulness for developing road safety policies and making well-informed decisions.

3. Data and Discussion

3.1. Overview

Following the scope of this study, an analysis of official statistical data from road crashes in Greece is made for the period 2016–2022. First, an overview of total road crashes and fatal crashes is given in Tables 1 and 2 per road category according to the process followed by the police, during the crash reporting and recording procedures. The percentages shown in Table 2 correspond to a specific road category and year; for instance, in 2016, the rate of fatal crashes on freeways was 38/284, or 13.4%.

Table 1. Official records of total and fatal crashes [27].

Road Category	Total Number of Crashes							*Number of Fatal Crashes*						
	2016	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	***2016***	***2017***	***2018***	***2019***	***2020***	***2021***	***2022***
Freeways	284	313	354	279	210	281	312	*38*	*47*	*58*	*47*	*31*	*35*	*42*
Intercity highways	1173	994	942	800	581	723	793	*232*	*213*	*142*	*151*	*106*	*119*	*134*
Local roads	1183	1092	1138	1072	709	1043	1114	*192*	*166*	*155*	*166*	*128*	*167*	*159*
Municipal roads	8632	8404	8252	8496	7512	8344	8184	*300*	*239*	*273*	*271*	*268*	*253*	*268*
Other	46	45	51	65	71	63	84	*10*	*14*	*17*	*21*	*19*	*10*	*16*

Table 2. Percentage of fatal crashes per year and road category.

Road Category	2016	2017	2018	2019	2020	2021	2022
Freeways	13.4%	15.0%	16.4%	16.9%	14.8%	12.5%	13.5%
Intercity highways	19.8%	21.4%	15.1%	18.9%	18.2%	16.5%	16.9%
Local roads	16.2%	15.2%	13.6%	15.5%	18.1%	16.0%	14.3%
Municipal roads	3.5%	2.8%	3.3%	3.2%	3.6%	3.0%	3.3%
Other	21.7%	31.1%	33.3%	32.3%	26.8%	15.9%	19.1%

As can be seen, crashes are more frequent on municipal roads, which implies urban areas; a fully anticipated result because of the higher number of conflict points within an urban road network. However, fatal crashes on municipal roads are of marginal magnitude compared to the rates shown in Table 2 for the rest of the road categories. This is mainly because of the higher speeds that vehicles can reach while travelling outside an urban area, thereby resulting in crashes with much more intensity. Focusing, on the first three road types, data are also given in Figure 6 (total crashes on the left axis, fatal crashes on the right axis), from which it can be stated that the rate of fatal crashes on freeways is nearly stable over the investigation period, whereas on intercity highways and local roads, there is a tendency for a progressive decrease in the percentage of fatal crashes.

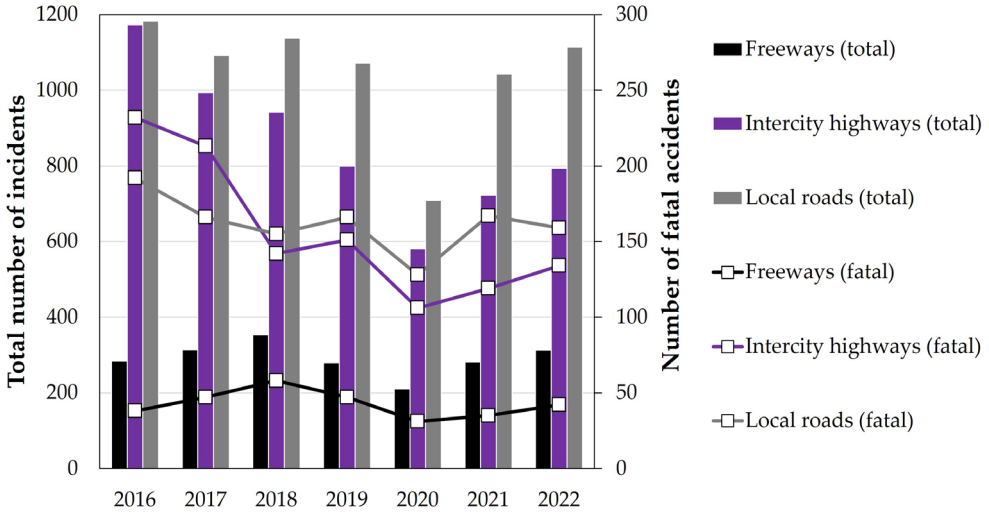

Figure 6. Evolution of total and fatal crashes on non-urban roadways (bars for the left vertical axis and lines for the right vertical axis).

The lowest number of total crashes as well the lowest rate of fatal crashes was observed in 2020, probably because of the COVID-19 pandemic period. Nevertheless, from Figure 6, it can be argued that the road status upgrade because of the construction of core freeways in Greece during the last two decades led to the descending trend in the rate of fatal crashes on the rest of the regional road network. Nevertheless, a potential future focus for

road redesign procedures should be put on that type of roadway, as in absolute numbers, non-freeway crashes are of a considerable amount.

3.2. Surface Status

Following the description of the impact of pavement surface characteristics, the total number of incidents is now distributed under various road surface conditions, including normal (dry) surfaces, wet surfaces, surfaces contaminated with oil or dust, icy surfaces, and snowy surfaces. It is noted that no roughness or other distress data are provided in the datasets of [27]. Given this, results related to the road's surface are given in Tables 3 and 4.

Table 3. Distribution of annual total and fatal crashes per year and road surface condition [27].

Road Surface Status	Total Number of Crashes							*Number of Fatal Crashes*						
	2016	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	*2016*	*2017*	*2018*	*2019*	*2020*	*2021*	*2022*
Normal (dry)	10,416	10,020	9825	9740	8442	9708	9809	*685*	*599*	*569*	*586*	*505*	*515*	*568*
Wet	810	721	826	847	555	648	601	*79*	*73*	*71*	*63*	*41*	*65*	*45*
Contaminated	28	27	33	29	24	28	23	*1*	*0*	*1*	*0*	*1*	*0*	*0*
Icy	32	32	16	27	11	9	11	*3*	*5*	*3*	*2*	*2*	*0*	*1*
Snowy	18	39	25	33	23	38	24	*2*	*1*	*0*	*1*	*0*	*4*	*1*
Other	14	9	12	36	28	23	19	*2*	*1*	*1*	*4*	*3*	*0*	*4*

Table 4. Percentage of fatal crashes per year and road surface condition.

Road Surface Status	2016	2017	2018	2019	2020	2021	2022
Normal (dry)	6.6%	6.0%	5.8%	6.0%	6.0%	5.3%	5.8%
Wet	9.8%	10.1%	8.6%	7.4%	7.4%	10.0%	7.5%
Contaminated	3.6%	0.0%	3.0%	0.0%	4.2%	0.0%	0.0%
Icy	9.4%	15.6%	18.8%	7.4%	18.2%	0.0%	9.1%
Snowy	11.1%	2.6%	0.0%	3.0%	0.0%	10.5%	4.2%
Other	14.3%	11.1%	8.3%	11.1%	10.7%	0.0%	21.1%

Excluding the normal (dry) surface and the "other" surface, an increased rate of crashes is observed on wet road surfaces. Grouping the categories "wet, contaminated, icy, and snowy" as abnormal surface conditions, it appears that nearly 90% of the total crashes occur on wet surfaces (Table 3, left part), whereas 10% occur on contaminated, icy, or snowy surfaces. This rate seems to be constant over the years. Noticeably, nearly 7–10% of "wet" crashes are fatal (Table 4). Focusing on the impact of wet surfaces (recall Figure 1), the amount of water that is present on the road's surface is critical for the vulnerability of a particular subsection. Figure 7 demonstrates the comparison between crashes because of a short rain shower versus crashes because of rainfall. Note that the annual sum shown in Figure 7 is lower than the "wet" crashes of Table 3, since Table 3 is related to crashes that may have occurred on a wet surface, including those after the rainfall event, whereas Figure 7 includes only those occurred during the climatic events.

From Figure 7, it can be observed that a surface with wet dust is much more dangerous for crash generation than a fully wet surface. Drivers might overlook the previously mentioned condition of "summer ice" described in the literature. This is the phenomenon when a road surface becomes very slippery because pre-existing contaminants, dust, or other loose debris on the road surface are mixed with a small amount of water because of short rain showers, thereby resulting in a surface with poor skid resistance and a reduced braking capability. Drivers may erroneously maintain their speed, and as a consequence, they can be involved in road incidents much more easily.

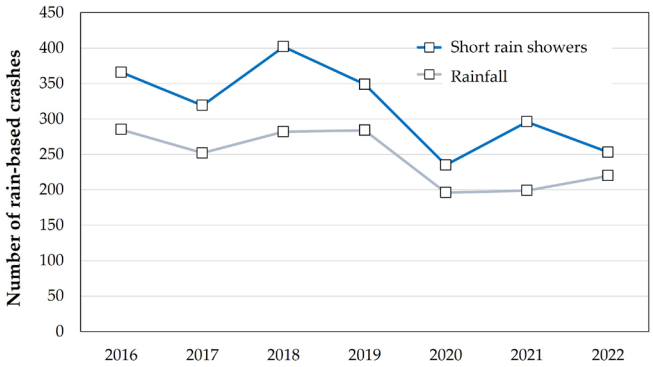

Figure 7. Crashes because of climatic events including short rain showers and rainfall.

Road authorities may also frequently overlook this factor, which can be eliminated by properly cleaning the surface at periodical intervals, especially after a prolonged dry period, by using routine maintenance methods (e.g., water blasting) in advance. Basically, in Greece some road authorities occasionally incorporate surface cleaning into their maintenance schedules mainly in the case of motorways. This is deemed much more necessary, especially in the case of tunnels, where the road surface cannot be completely dried and cleaned after a rainy event. However, for the rest of the roadway network, this still remains an issue because of the criticality of crashes during rainfall. It is noted that nearly 7% to 11% of the rain-based crashes in Greek territory are fatal according to [27].

3.3. The Role of Lighting and Signage

As previously explained, lighting conditions are related to the visibility of drivers, whose directional and maneuvering capabilities can lead to a considerable number of crashes. Data about crashes because of visibility conditions are given in Tables 5 and 6. Because of different data availability patterns for this condition status, the number of deaths was given in [27] instead of the number of fatal crashes shown in the previous subsections. So, a slightly different concept is presented in Table 6 that gives the "crash repetitions" per one death. A nearly constant frequency of 15–20 crashes is observed for cases of sufficient physical lighting (i.e., daytime and dusk). Sufficient lighting at nighttime can have an equivalent performance in terms of fatal crash frequency with those during daytime.

On the contrary, a considerable difference is observed during nighttime under no lighting conditions, where nearly one death is recorded every four crashes. Noticeably, the inadequacy or the malfunction of lighting results into a considerable rate of fatal crashes, i.e., one death is recorded every 5–10 crashes. This can provide a significant remark for the related authorities and decision-makers about the impact of good lighting conditions. Low or inadequate lightning, as well as the complete absence of lighting, does not satisfy drivers' needs and may alert for investments and greener solutions to ensure lighting through smart and cost-effective illumination systems, like the one suggested by Figure 4. As a result of good lighting, visibility can be improved and road collisions might be reduced.

Table 5. Distribution of annual total crashes per year and visibility conditions [27].

Visibility Status	Total Number of Crashes						
	2016	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**
Daytime	7341	7136	7058	7019	5991	6907	6778
Dusk	614	566	579	532	508	546	553
Nighttime, sufficient lighting	2553	2420	2379	2418	2027	2421	2548
Nighttime, insufficient lighting	411	387	392	404	283	335	285
Nighttime, out of order lighting	63	42	50	45	37	30	40
Nighttime, no lighting	336	297	279	294	237	254	299

Table 6. Crash occurrence per deaths (i.e., one death per *X* crashes or else fatal crash frequency).

Visibility Status	Number *X* of Crashes per One Death						
	2016	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**
Daytime	16	17	17	18	18	20	18
Dusk	17	16	18	17	17	16	15
Nighttime, sufficient lighting	15	17	19	19	17	17	19
Nighttime, insufficient lighting	6	7	7	8	9	10	7
Nighttime, out of order lighting	5	4	6	5	5	8	8
Nighttime, no lighting	4	4	4	4	4	4	5

Proper design of signage can be extremely useful for drivers, especially for those belonging to vulnerable categories (i.e., younger or elderly drivers), or for those who are new drivers in a particular area, and thus not fully familiarized. Moreover, a roadway path should be self-explaining for all drivers irrespective of their age or driving experience. Absence of signage or mal-design of road signs raises the potential for crashes, especially within urban areas because of the increased number of conflict points [81]. The interaction with pedestrians is also another aspect to consider in terms of strictly selecting and placing related signage.

In [27], information about signage comes from a category named "traffic regulation: markings and signaling". Subcategories include police enforcement, visible or invisible traffic signals, visible or invisible signs for stoppage, signage for sharp horizontal and vertical curves, etc. Based on the subcategories that account for a considerable number of crashes, such that meaningful conclusions can be made, those appearing in Figure 8 prove that most crashes occur in areas with visible traffic signals or visible stoppage signs. This fact implies that road crashes are more likely to occur in urban areas with many intersections, something which confirms the statistics given in Table 1.

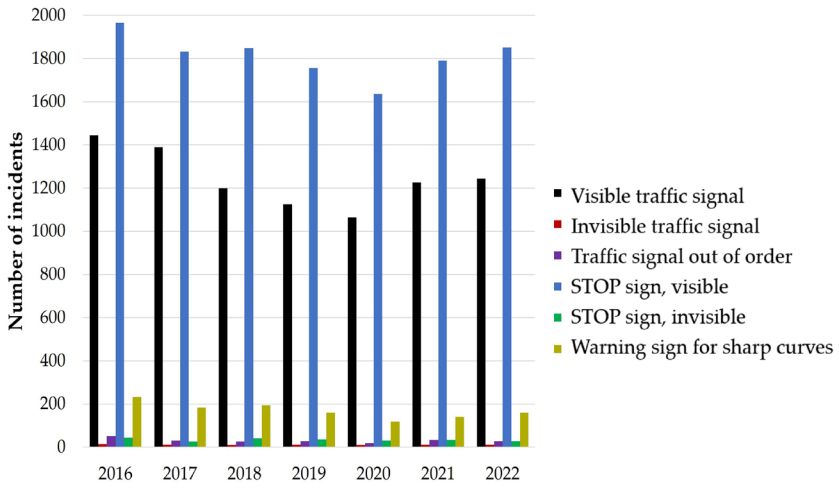

Figure 8. Crashes because of traffic regulatory measures (signals, signage, etc.).

According to Figure 8, a first reaction creates controversy considering that signing is visible. Upon closer inspection, the results could be impacted by the fact that most incidents occur on municipal roads (recall Table 1), where a number of factors, including signage, could contribute to the incident. Despite their visibility, the high number of incidents may suggest that suitable and effective signage design and placement need to be reconsidered, and more research and implementation should be carried out in this area.

Finally, identifying black spots in an urban area could help locate the exact points where re-assessment of the existing signage efficacy is needed. Moreover, the execution of black spot analysis can help identify a weak road or a traffic design that requires redesign assessment [82]. For the sake of completeness, it is noted that apart from infrastructure-based interventions, some additional behavioral driving patterns have been proposed to improve drivers' safety, like the speed limit of 30 km/h in urban areas [83].

3.4. Geometric Characteristics of Road Design

Inevitably, road geometrics are the key factor for designing safe infrastructure. As explained earlier, several design features have been found to correlate to some extent with safe driving conditions and accident ratio, including among others curve radii, number of lanes, superelevation, existence of emergency lane, slope, speed limit, etc. [49,84]. For the present study, the contribution of each sole geometric category is shown in Figure 9. The available statistics provide evidence that the majority of incidents occurs in the case of straight alignment, followed by at-grade intersections.

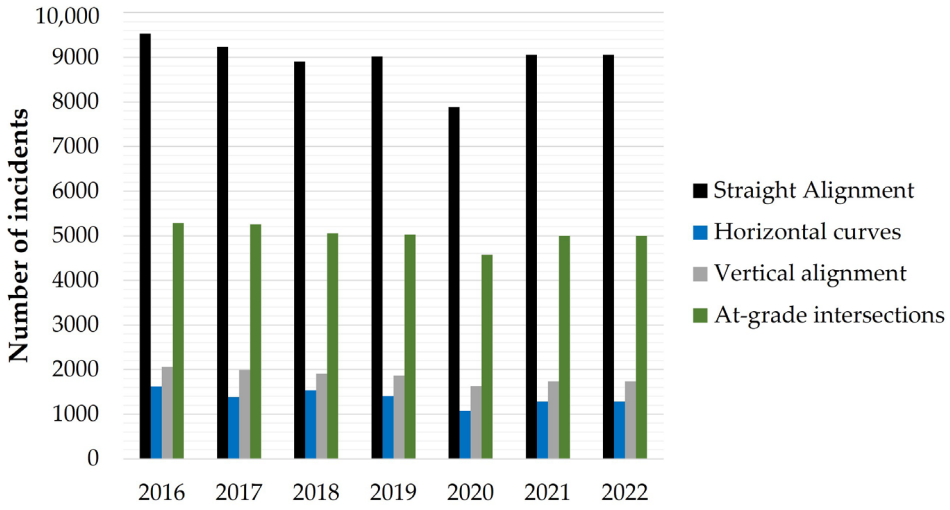

Figure 9. Crashes per different characteristics of road geometric design.

An issue with this discrimination is that it difficult to organize network-level data much more precisely, such that different combinations of vertical and horizontal alignment could form additional subcategories. In other words, the bars in Figure 9 provide duplicate information, considering that an individual crash on both horizontal and vertical curves has been counted double. This is why tables depicting total and fatal crashes cannot be shown at this stage alike the previous analysis steps, because they might provide some duplicate information and could mislead the reader. Furthermore, the combination of a location at an intersection and in the area of a horizontal curve could also account for a considerable number of crashes. This means that many more additional categories could be formed. Nevertheless, in order to extract some information about the criticality of road design aspects, crash data per geometric design category are given as a percentage out of the total number of crashes per year in Table 7.

Table 7. Percentage of crashes per year depending on the geometric design feature.

Geometric Characteristic	2016	2017	2018	2019	2020	2021	2022
Straight Alignment	84%	85%	83%	84%	87%	87%	86%
Horizontal curves	14%	13%	14%	13%	12%	12%	12%
Vertical curves	18%	18%	18%	17%	18%	17%	17%
At-grade intersections	47%	48%	47%	47%	50%	48%	48%

From Table 7, the following remarks can be made:

- The overwhelming majority of road incidents take place on straight alignments, probably because drivers overestimate their capabilities and increase their moving speed. This is why many international design standards for roads alert for a maximum length of straight alignment, e.g., [85], to avoid leaving drivers to navigate there for a long time. Although there might be cases when the previous remark is violated, there are solutions to limit or at least control the increased crash rate on straight alignments. These could include refining signage and road markings to help drivers adapt to the current road environment, and much more law enforcement and police patrols that could help drivers adopt a different behavioral perspective while driving. Moreover, reconsideration of speed limits could help drivers better understand the environmental component of safe driving, because of the lower pollutant emission and fuel consumption that could save money. It is noted that the rate of fatal crashes on straight alignments falls in the range of 4–6%;
- Nearly one out of two incidents occur as a result of at-grade intersections. Hopefully, only 3% of them are fatal accidents, and this rate appears to be constant over the investigation period. Profoundly, a considerable rate of these crashes belongs to the subcategory of straight alignment too. A limitation of the available data is the inability to discriminate what portion of the intersection-related crashes is in urban areas or not. Nevertheless, since intersections are characterized at an international level as black spots for incidents, they still pose a significant risk to the public, which often leads to serious accidents between road crossings, or even road and rail crossings. This should alert the related authorities about the need to upgrade the existing vehicle interaction system at intersections, by integrating modern design perspectives (e.g., roundabouts, etc.) and novel technologies. These could include smart lighting, proper road markings, and improved guide signs to provide a better directional management of the vehicle position, especially for vulnerable road users trying to interact with surrounding vehicles and/or pedestrians as well;
- The horizontal and vertical profile of a roadway appears to cause the lowest percentage of the total crashes (recall Table 7). However, nearly 10–15% of them are fatal. This proves the criticality of road accidents on curves, thereby emphasizing the necessity for a continuous and well-planned upgrade of the existing road network on curves. Of course, a complete road redesign in such cases might be impossible because of budget constraints, terrain configuration, limitations due to expropriations, and relief constraints that could require costly technical works, like bridges or tunnels, etc. Nevertheless, more minor, yet strategic interventions could mitigate the road crash potential, like (i) the use of HFST courses to ensure skid resistant road surfaces near curves, or areas with high longitudinal slopes, (ii) the improvement or complete replacement of signage and road markings, (iii) the reconsideration of speed limits, as well as (iv) the proper lighting of critical roadway segments to ensure visibility at nighttime.

4. Conclusions

4.1. Main Remarks

A multitude of research and experience has shown that a scientific, rigorous, consistent, and proactive approach to highway planning and design may considerably improve overall driver safety. Given the expense of engineering studies and limited funding, simulation studies, ad hoc safety evaluations, on-site inspections, and reviews of available historical data are among the major practices to follow in order to propose engineering remedies and improve the crash susceptibility of high-risk road subsections. This study used network-level historical records of crashes in the Greek territory over a seven-year period, and proposed four core and contributing pillars on which the focus for future road redesign planning could be put. These were all related to the road infrastructure status and included:

- the need to preserve adequate performance status of the road surface, which indicates the necessity for skid resistance measures at periodical intervals in order to plan any kind of restoring interventions;
- the need to ameliorate the signage and lighting status on the entire road network with an emphasis on high-risk locations;
- the need to improve the driving conditions near at-grade intersections, by improving signage, road markings, and lighting, and examining the potential for transforming core intersections into roundabouts; and
- the ability to intervene, to some extent (if possible), given several techno-economical constraints, at specific road segments because of current questionable design features. It is noted that the purpose of this study was not to propose specific segments that are subject to improvement. Moreover, the implementation scale is a multi-parametric task that requires a multitude of information with road design and geolocation data that were absent from the online dataset of crash records. This should be acknowledged as a study limitation.

The ultimate goal of these intervention pillars is to stress the importance of a good infrastructure status irrespective of the behavioral component of driver safety; or in other words, the target is a well-maintained road surface and a self-explaining road design that can jointly ensure improved directional capabilities of all drivers, thereby resulting in fewer crashes, or more accurately, fewer fatal crashes.

4.2. Challenges and Prospects

Actions for at least one of these pillars should aim at enhancing the safety and functionality of roadways. Towards this, the following challenges are mentioned when moving from a strategic planning to an implementation scale:

- data should be oriented from project-level records and reporting to identify a list of the most hazardous sites;
- crash data should be collected and reported through a standardized procedure including as much and as accurate information as possible, by experienced personnel;
- a prioritization process should follow for the scheduling of the most cost-effective redesign projects.

Overall, once crash data are to be used for research purposes by engineers and for selecting intervention actions by policy-makers and road stakeholders, a robust procedure to collect, manage, analyze, and interpret data is important. It is to be noted that although the trigger for this research was data coming from a single country, the methodological approach presented should be replicated elsewhere, by redefining those pillars (or even identifying new ones) that are representative and adaptive to the conditions met elsewhere, including specifications for road design and maintenance.

Aspects of future research developments and prospects could include more detailed analysis of crash records homogenized for specific road types and design data (e.g., study of crashes on horizontal curves, vertical curves, straight alignments, etc.), so that more informative conclusions can be drawn, and more targeted recommendations can be made, especially for the pillar of road redesign, which is the most difficult to achieve and implement. More in-depth cross-referenced data might be needed to perform advanced statistical analysis and verify the sole and joint impact of the contributing factors to road incidents.

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