Traffic & Transportation

Heinrich's Law for Traffic Incidents – Using the Digital Tachograph Data to Identify Traffic Accident Hotspots

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ABSTRACT

Heinrich's Law indicates an empirical ratio between serious accidents, minor accidents and near misses in industrial sites, but has not been discussed in the context of road traffic accidents. Digital tachographs (DTG), a type of IoT device collecting spatiotemporal big data of vehicle trajectories, allow0 for examining a linkage between abnormal driving behaviours and the prevalence of road traffic incidents. According to the Traffic Safety Act implemented in 2011, DTG has been mandatorily pre-installed on most commercial vehicles in South Korea. The data have been analysed to evaluate the data processing method or promote eco-driving or safe driving, but only a few studies have examined an association between driving behaviours and actual traffic accidents using the limited data. We obtained 7,785,124 DTG sensing records from 1,523 commercial taxis driving within the city limits of Seoul at least once in 2013 and integrated them with 57,139 traffic accident cases during the same period. Using the integrated GIS database, we performed a grid-based spatiotemporal mapping and analysis to calculate a ratio among abnormal driving events, minor and major traffic accidents by road type. The findings suggest a potential for enhancing road safety by monitoring and controlling abnormal driving patterns as a precursor for accidents.

KEYWORDS

traffic accident; spatiotemporal; digital tachograph; driving behaviour; road safety policy.

1. INTRODUCTION

Road traffic injury (RTI) is a major public health threat and accounts for a significant source of disability in both developing and developed nations [1, 2]. These incidents are responsible for 2.1% of global mortality and 2.6% of all disability-adjusted life years lost [3]. This can be due to a multitude of factors, including social, economic, physical, environmental factors, as well as human factors that relate to driving behaviour [4], but particularly in developing countries, mostly relating to the lack of infrastructure and allocation of resources that can improve driving and road conditions [5, 6]. Low- and middle-income countries account for almost 90% of the global mortality due to RTI [7], but the RTI burden is not only a public health threat in developing countries but also in developed nations [8]. For instance, South Korea had one of the highest RTI mortality rates among the OECD (Organisation for Economic Co-operation and Development) countries, due to various risk factors associated with increased severity of pedestrian injury such as intoxicated drivers, road-crossing pedestrians, elderly pedestrians, heavy vehicles, and road and weather conditions [9, 10]. RTI ranks as the second leading cause of death among individuals aged 1-29 years and the third leading cause among those aged 30-39 years [10]. Given the exceptionally low facility rate in this country (0.78 in 2022), these statistics underscore the urgent need for comprehensive measures to address and mitigate the impact of RTI on these vulnerable age groups. The OECD report of traffic safety in South Korea notes that South Korea's rapid economic development over several decades was paired with road expansion, motorisation and more traffic, which explains the higher rates in roadside accidents, injuries and fatalities in the country [11]. This report, however, highlights driving behaviour and speed as one of the most common determinants of the roadside crashes in South Korea. One study describing road traffic injuries identified various types of risk factors using the Haddon matrix, a model which distinguishes between the host (humans), agent (vehicles and equipment) and the specific environmental conditions present during the accident (physical and socioeconomic) [12]. It also categorised various risk factors for RTI into pre-crash (speed, driving while impaired or being young), crash (failure to use seatbelts and poorly designed roads or low visibility), and post-crash (trauma and emergency care services for crash victims), which makes it easier to identify the causes and thus implement a more targeted intervention plan.

Although there is abundant research and statistics that emphasise the severity of this threat highlighting the urgent need for policy intervention to help control the rate of RTI, there is still a need to understand the relationship between various abnormal driving behaviours and the rate of major or minor injuries. Among a number of theories that attempt to explain factors causing RTI with an aim to design policies to prevent future accidents, Saxena (2017) identifies the Domino Theory of accidents [13]. This theory recognises the role of multiple "dominoes" such as social environment, the fault of the person and unsafe conditions, which lead to accident and injury. A few other theories included in this discussion are the role of human error in accident modelling which solely considers the behavioural aspect of accidents, as well as the risk homeostasis theory which uses circular causality to link changes in perceived risk and behavioural changes to explain the rate of accidents. However, these theories failed to provide empirical evidence to explain the role of driving behaviours on actual RTI outcomes.

Recent case studies provided some empirical evidence using various models. Peralta-Sanotos et al. (2022) analysed risk factors associated with road traffic injuries in Mozambique, focusing on urbanicity, ownership of a car or motorcycle and socioeconomic strata index in their analysis [14]. The study found a 47% decrease, 92% increase and 26% decrease in the rate of RTI for urban residence, motorbike ownership and high socioeconomic status, respectively. The results from this study showed that RTI is a complex public health issue, with more than one cause including personal and behavioural factors. Besides, Raman et al. (2022) used a Bayesian belief network model to investigate the complex linkages between driving behaviour and the causes of RTI in Saudi Arabia [15], while Rachad et al. (2023) used the survey data from the Driver Behaviour Questionnaire in Morocco and found that accidents are closely related to driving experience and concentration while driving [16]. While these case studies provide intriguing insights, there remains a pressing need for data-driven empirical studies founded on robust theoretical frameworks, elucidating the precise relationship between human behaviours and specific accident types.

Heinrich's Law is explained using an accident triangle to illustrate the probability of various types of injuries resulted from accidents. It is claimed as the basis for the theory of behaviour-based safety, which posits that most of all workplace accidents are caused by unsafe acts. Specifically, Heinrich proposed a ratio relating to the number of near miss incidents and minor harm injuries to a single major harm injury and summarised this as 300:29:1 [17]. In his 1931 book, he shared the insights that, for each major injury accident, there are approximately 29 incidents resulting in minor injuries and around 300 incidents causing no injuries [18]. This proportion, commonly referred to as the "1-29-300" ratio, provides valuable context to understand the frequency and severity of workplace accidents. The claim of this law that a decrease in minor accidents is followed by a decrease in serious fatal accidents has been evaluated and found valid in the literature of occupational safety [19], which confirms that Heinrich's pyramid could be a useful signal for forecasting and predicting safety performance. Heinrich's Law has been applied to industrial accidents (i.e. a serious event that can have consequences for the surrounding population or environment in an industrial site), but could be relevant to other types of accidents, such as road traffic accidents.

Despite the importance of monitoring abnormal driving behaviours as a precursor for actual traffic accidents, the real-time driving data has not been widely available due to the difficulty in processing enormous amounts of data, which makes it difficult to effectively implement surveillance and monitoring systems. A digital tachograph (DTG) is an IoT device responsible for collecting spatiotemporal data of vehicle trajectories and can serve multiple purposes that can help improve vehicle routing, driving education, and traffic safety regulation. These devices are becoming widely common in many parts around the world, with regulation agencies in Europe and South Korea mandating DGT's in trucks and new business vehicles, respectively [20]. In South Korea, for instance, DTG devices have been used to record real-time data for taxis and busses including speed, brake signal, vehicle position and acceleration [21]. The resulting database could be useful, not only for determining the status of vehicles upon crashing, but also for designing traffic safety education for bus drivers to prevent future accidents. However, there has been no comprehensive empirical study that integrates this data with the actual accident records to understand their spatiotemporal association and explore the predictability of driving behaviours on traffic accident patterns and hotspots.

Our study builds on the part of Heinrich's pyramid that states that major accidents are not always sudden but may be the consequence of other minor events like abnormal driving behaviours [22], and thus attempts to verify if the basis for Heinrich's law seems promising in its ability to be applied to road traffic incidents. We integrate the DTG data with the RTI data from Seoul, Korea to understand the spatiotemporal similarity patterns of major and minor road accidents along with abnormal driving behaviours. Then, we apply Heinrich's Law to identify a relationship between the types of accidents and different locations in which they occurred, with the goal of better understanding ways to monitor and control this rising concern in many countries around the world. Our study differs from others in its emphasis on Heinrich's law and the method in which it can be applied to better identify RTI risk hotspots by road type. Moreover, there is limited literature on Heinrich's theory, especially relating to how it can be used to understand the linkage between traffic accident patterns and abnormal driving behaviours. The findings of this study will showcase the application of grid-based spatial big data mapping in identifying hotspots of behaviour-related RTI, offering valuable insights to mitigate these public health risks effectively.

2. METHODOLOGY

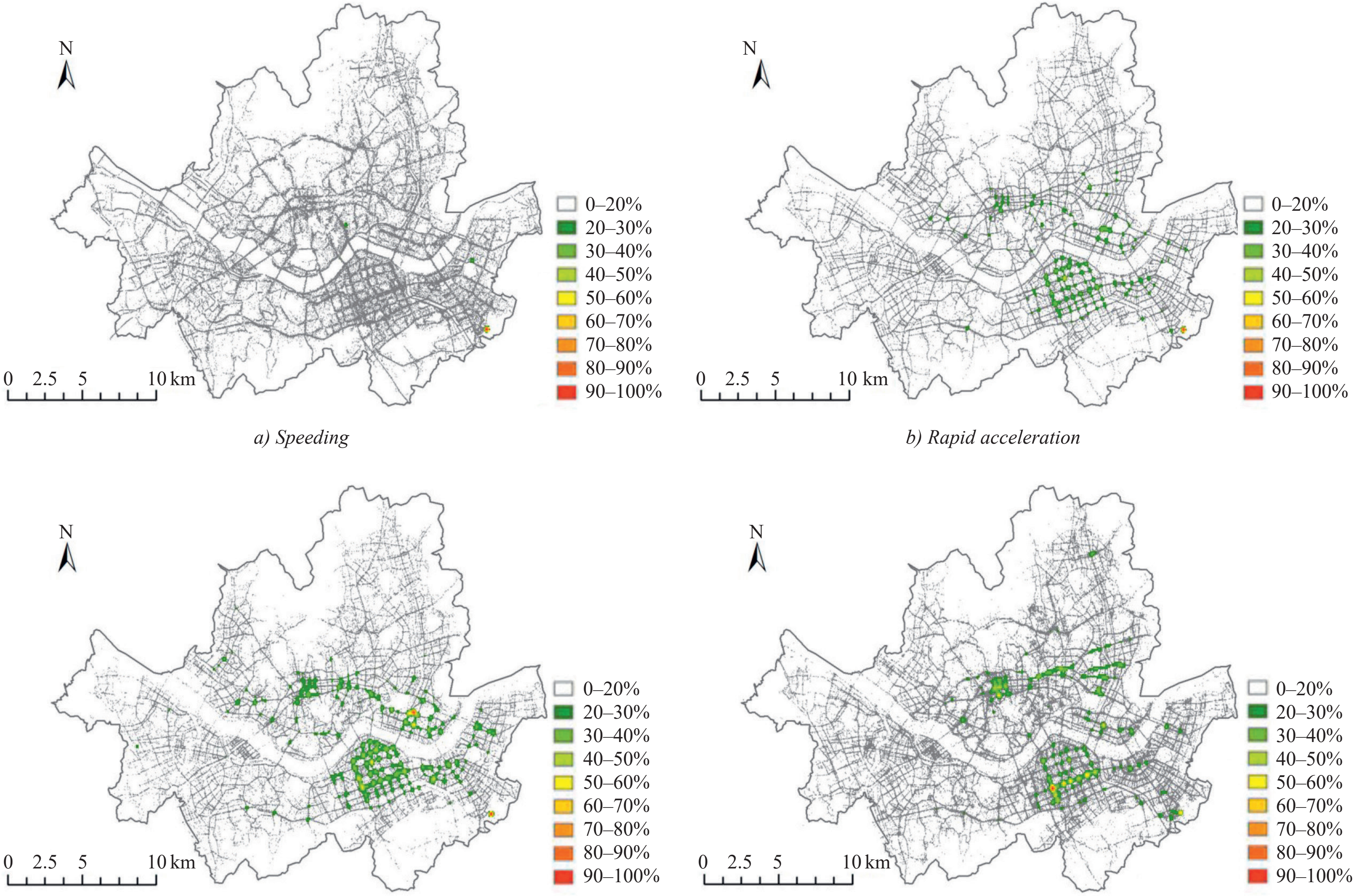
According to the Traffic Safety Act implemented in 2011 in South Korea, DTG has been mandatorily pre-installed on most commercial vehicles. A large volume of GPS data generated from the devices along with various operating history of the vehicle could be utilised for multiple purposes, such as vehicle routing, driving education and traffic safety regulation. The data has been analysed to evaluate the traffic patterns or promote eco-driving or safe driving [23–25], but only a few recent studies have examined an association between driving behaviours and actual traffic accidents using the limited data [26, 27].

We obtained 7,785,124 DTG sensing records from TS Korea Transportation Safety Authority for 1,523 commercial taxis driving within the city limits of Seoul at least once between 1 January and 31 December 2013 and integrated them via spatial join with 57,139 traffic accident cases collected by the Korea Road Traffic Authority during the same period. A total of 378 "major" accidents involving fatality and 56,761 "minor" accidents without any death were recorded during the study period and used for the analysis. A series of maps for abnormal driving behaviours, classified as acceleration-related, deceleration-related and steering-related, were created for the city of Seoul illustrating interesting spatiotemporal patterns when compared with those for accidents. Abnormal driving events recorded by DTG include speeding, rapid acceleration, rapid start, rapid deceleration, rapid stop, rapid right turn, rapid left turn and rapid overtake.

GIS-based spatiotemporal analyses were then conducted on square grids to detect any potential significant association between abnormal driving behaviours and the two types of accidents by severity. To evaluate the so-called Heinrich's ratio for road traffic injury in Seoul, three different time radii (30, 60 and 90 minutes) and spatial radii (300, 500 and 1,000 meters) were constructed from every "major" accident point in time and location in space, to count the number of "minor" accidents and abnormal driving episodes detected by DTG within each spatiotemporal radius. After conducting a series of sensitivity analyses involving 9 distinct spatiotemporal units, the main findings were found consistent. Consequently, we selected a 500 by 500-meter grid for a 60-minute timeframe as the basis for our analysis. Within each spatiotemporal grid, we computed the ratios encompassing major accidents, minor accidents and instances of abnormal driving behaviours by five different road types such as crossroad, crosswalk, hump, subway and school zone. All spatial data processing and computations were conducted by Python 3.6. Ethical approval was not required because this study did not involve human participation and used secondary data.

3. RESULTS

Figure 1 shows the point-pattern maps of Seoul illustrating spatial patterns of four different abnormal driving behaviours including (a) speeding, (b) rapid acceleration, (c) rapid stop and (d) rapid turns. The overall patterns are similar with hotspots found in the southeaster parts of the city, but the detailed scope of the distribution



a) Speeding

b) Rapid acceleration

c) Rapid stop

d) Rapid turns

Figure 1 – Spatial distribution of abnormal driving patterns by type at the district level in Seoul

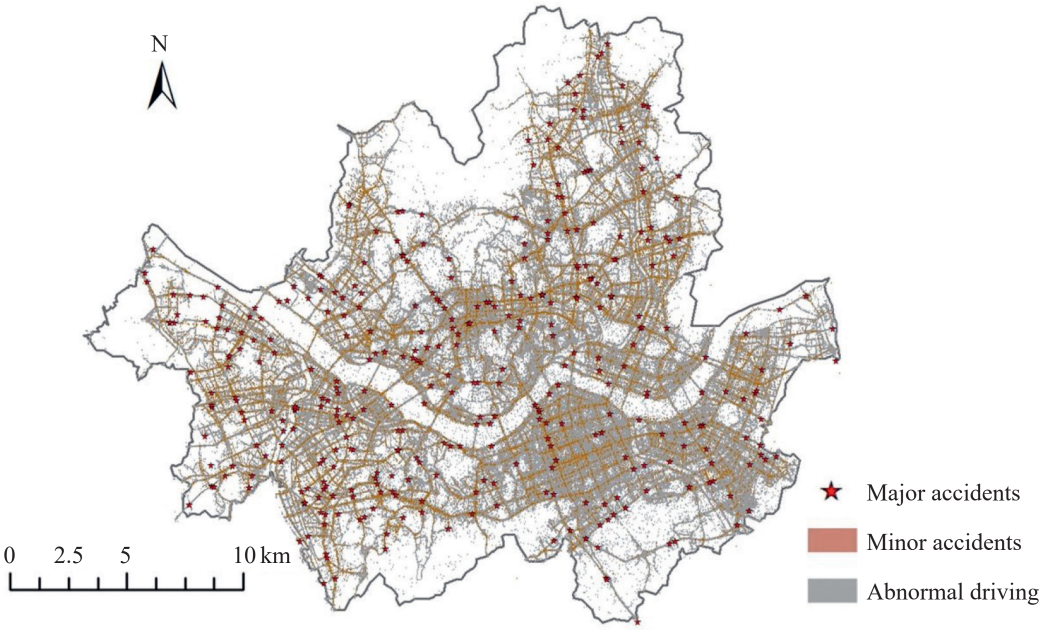


Figure 2 – Spatial distribution of major and minor road traffic accidents and abnormal driving episodes in Seoul

looks somewhat different by specific types of driving behaviours, implying unique spatial characteristics of different driving behaviours. *Figure 2* illustrates the overall distribution and trends of major and minor accidents throughout the city, while also accounting for abnormal driving episodes. It appears from the map that both types of accidents are prevalent throughout the city but there is some evidence of clustering, although the specific patterns are not distinctly visible due to the large amount of data. However, it clearly illustrates that the accident data, both major and minor, corresponds to abnormal driving, revealing a potential spatiotemporal association with these types of accidents.

We used a total of 2,635 500m´500m grids, spanning across the entire city of Seoul, for subsequent analyses to explore potential associations between abnormal driving behaviours from DTG data and accidents at the grid level. *Table 1* presents descriptive statistical results regarding traffic accidents categorised into three severity levels (accident involving light injuries, severe injuries and deaths), along with four types of abnormal driving behaviours (speeding, rapid acceleration, rapid stop and rapid turn), all aggregated at the grid level.

Table 1 – Grid-level descriptive statistics of traffic accidents and abnormal driving behaviours by type

	Traffic accidents involving			Abnormal driving behaviours			
	Light injury	Severe injury	Death	Speeding	Rapid acceleration	Rapid stop	Rapid turn
	19.6	8.37	1.22	11,439	190.3	24,054.4	12,196.7
	19.1	7.12	0.48	297,765	325.2	681,192	394,198
	1	1	1	0	0	0	0
	14	6	1	88.5	60.5	31	15
	147	46	3	11,336,138	5,191	20,232,131	15,065,236

Figure 3 shows a scatterplot showing a grid-level bivariate association between the number of abnormal behaviours and the number of three different severity levels of accidents, counted on each grid created over the entire city. The red line represents a linear trend line for each severity category, illustrating the overall pattern and strength of association. Although not statistically strong, the positive association is noticeable for all three types of accidents, with a larger slope for the accidents involving deaths or severe injuries ("major accidents") than those involving light injuries ("minor accidents").

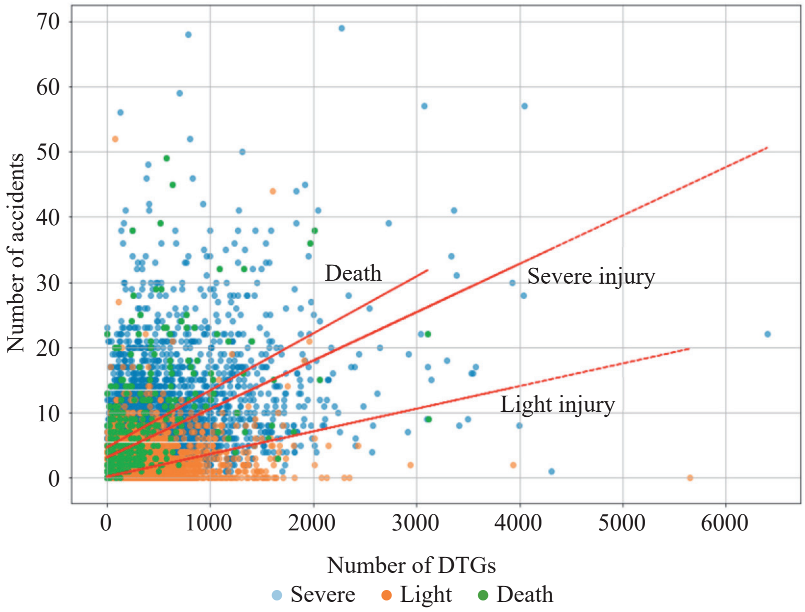
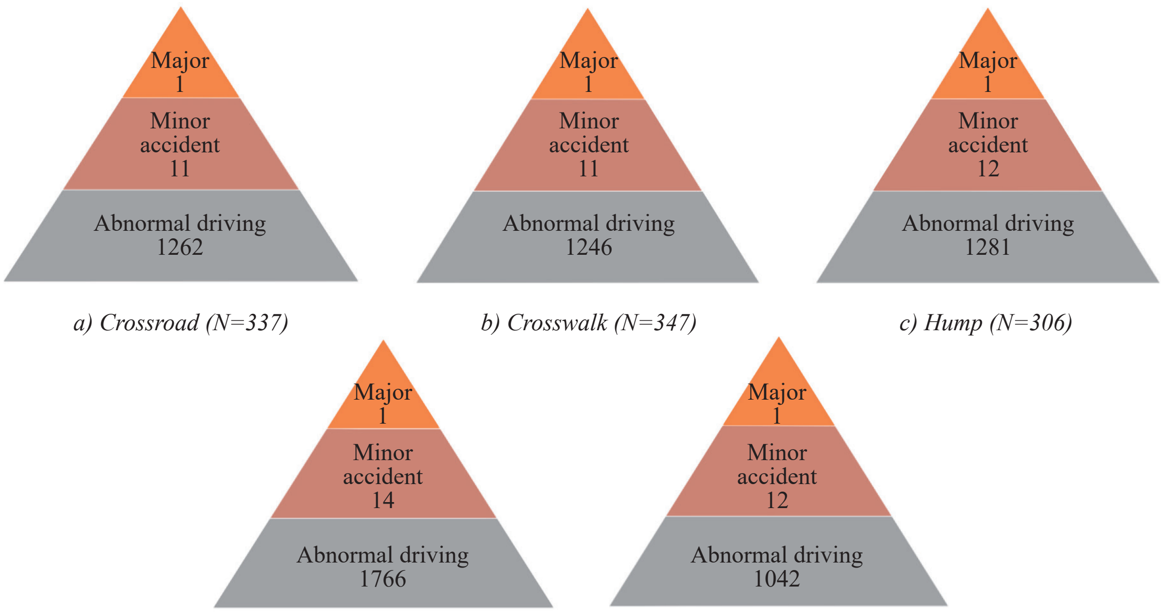


Figure 3 – Scatterplot showing bivariate association between abnormal behaviours and different types of accidents

Figure 4 shows the five representations of Heinrichs's pyramid for road traffic accidents, divided by road type, and highlights the ratio between major accidents, minor accidents and abnormal driving occurrences. When comparing these pyramids, *Figures 4a–4c* have similar ratios, but it seems that subway stations had the highest ratio between accidents, whereas school zones had the lowest. As for the comparison of these pyramids to Heinrich's original proposed ratio of 1:29:300, the second tier of all pyramids looks significantly smaller than Heinrich's original accident triangle for industrial accidents while the bottom tier looks substantially larger. In other words, for one major traffic accident, there were 11–14 minor traffic accidents (compared to 29 in Heinrich's Law) and 1042–1766 instances of abnormal driving behaviours (compared to 300 in Heinrich's Law) across all road types. It seems evident that the ratio of minor accidents in all pyramids of *Figure 4* are almost half of the original ratio, which may be due to the difference in how we defined minor accidents. Additionally, the third tier, abnormal driving episodes, reveals a large variation compared to the original ratio, being almost 4–5 times higher than the proposed value of 300. This significant increase indicates that there is more abnormal driving and less safety behaviour practiced in road traffic sites, compared to industrial sites.



a) Crossroad (N=337) *b) Crosswalk (N=347)* *c) Hump (N=306)*

d) Subway station (N=178) *e) School zone (N=217)*

Figure 4 – Henrich's pyramid for road traffic accidents (ratio between major accident, minor accident and abnormal driving)

Altogether, all these spatial analyses and mapping exercises emphasise the widespread prevalence of road traffic incidents in the city of Seoul, and specifically, the association between minor and major accidents to abnormal driving. The distinct ratio of accidents and abnormal driving for each road type is crucial in aiding policymakers design programs to promote safer driving behaviours.

4. DISCUSSION

Heinrich's safety triangle has been applied only in terms of industrial accidents, such as incidents occurring at oil and gas sites, but has not been widely discussed in relation with road traffic accidents. Considering the possible similarities between industrial and traffic accidents in terms of behavioral risk factors, our study aims to explore the potential extension of Heinrich's law to identify a link between abnormal driving behaviors as near misses and the actual incidences of minor and major incidents in the same street locations. Since many experts claim Heinrich's work as the basis for the theory of behavior-based safety, we explored a potential for applying "Heinrich's law" in road traffic data research and practices, using the real-time driving records collected via DTG device installed in commercial vehicles. Although the exact replication of Heinrich's original ratio was not observed in our analysis of traffic accidents, the findings provide compelling evidence that the cumulative occurrence of abnormal behaviors can contribute to accidents resulting in minor injuries and, ultimately, accidents with major injuries. While the specific ratios may differ, the underlying principle remains evident, emphasising the importance of addressing and mitigating abnormal driving behaviors to prevent more severe accidents, which has been widely supported by the literature [28, 29]. In addition, our findings correspods to that of the recently-published study by Park et al. (2023) that found spatial associations between minor and severe police-reported crashes. They also echoed our argument that Heinrich's law has merit to apply in traffic safety [30].

5. CONCLUSION

It appears that GIS-based spatiotemporal mapping and analyis could play a role in detecting a possible connection between abnormal driving behaviors and actual road traffic accident events. Although the actual dynamics behind the linkage remain unknown and may require further investigation, this evidence-based efforts would enhance urban safety by proactively monitoring and controlling abnormal driving patterns as a precursor for various types of accidents. The findings from this explorary study would provide a useful guidance to policy makers when it comes to the identification of hotspot areas needing attention and the design of policy intervention and prevention programs to reduce the rates of major road traffic accidents involving fatality. While we acknowledge the inherent limitations of utilising 10-year-old data, we firmly believe that it still provides meaningful insights into the association between driving behaviors and traffic accidents, as well as the role of IOT-based driving sensing records. We are eagerly awaiting the release of more recent data to external researchers, as it would enable a comparative analysis to determine any potential temporal changes that have transpired over the past 10 years. This comprehensive examination will shed light on whether there have been any noteworthy shifts in the dynamics between driving behaviors and traffic accidents during this period. Another significant limitation of our study stems from the absence of car plate numbers or VIN numbers in the traffic accident data we utilised. This omission, most likely due to privacy concerns, prevented us from matching the DTG data with specific taxi vehicles to determine their involvement in traffic accidents during our analysis. However, considering that accidents involving taxis account for a significant portion of all automobile accidents in Korea [31], we believe that the data derived from traffic accidents involving commercial taxis can be considered reasonably representative of the broader scope of traffic accidents in Seoul.

ACKNOWLEDGEMENT

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조성환, 김도형, 히바 칸, 이창길

교통사고에도 하인리히법칙이 적용되는가? 디지털타코그래프 자료를 이용한 교통사고 핫스팟분석

추상적인

하인리히의 법칙은 산업 현장에서의 대형사고, 경미한 사고 및 사고직전상태 사이의 경험적 비율을 나타내지만, 도로교통사고에 대해서는 충분히 논의되지 않아 왔다. 디지털 타코그래프 (DTG)는 차량 궤적의 공간적 시간적 대량 데이터를 수집하는 IoT 장치 유형으로, 이를 바탕으로 비정상적인 운전 행태와 도로교통사고 패턴간의 연관성 분석이 가능해졌다. 2011년에 한국에서 시행된 교통안전법에 따라 대부분의 상용 차량에 대해 DTG가 의무적으로 사전 설치되면서 이 데이터를 바탕으로 안전 운전을 장려하는 연구는 일부 있었지만 운전 행태와 실제 교통 사고 사이의 시공간적 관계를 분석한 연구는 많지 않은 것이 사실이다. 본 연구는 2013년 서울시 내에서 적어도 한 번 운전한 1,523대의 상용 택시로부터 수집된 7,785,124건의 DTG 감지 기록을 동일 기간 동안의 57,139건의 교통 사고 자료와 통합하여 GIS 데이터베이스를 구축하고 이를 바탕으로 그리드 기반의 시공간적 맵핑 및 분석을 수행함으로써 도로 유형별로 비정상적인 운전행태와, 경미한 사고 및 대형 교통사고 간의 비율을 계산하였다. 본 연구의 결과는 교통사고의 선행 조짐으로서 비정상적인 운전 행태를 모니터링하고 제어함으로써 도로 안전을 향상시킬 수 있는 가능성을 시사하고 있다.。

키워드

교통사고, 시공간분석, 디지털 타코그래프, 운전행태, 도로안전정책。