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Driver Fatigue and Road Safety on Poland's National Roads

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This paper presents an overview of factors causing driver fatigue as described in the literature. Next, a traffic crash database for 2003–2007 is used to identify the causes, circumstances and consequences of accidents caused by driver fatigue on Poland's national roads. The results of the study were used to build a model showing the relationship between the concentration of road accidents and casualties, and the time of day. Finally, the level of relative accident risk at night-time versus daytime is defined. A map shows the risk of death and severe injury on the network of Poland's national roads. The paper suggests to road authorities steps to reduce fatigue-related road accidents in Poland.

driver fatigue road safety national roads

1. INTRODUCTION

Road transport is the predominant form of transport in many countries. For example, Europe carries 75% (based on tonne-kilometres) of its goods by road. The disproportion between modes of transport is even more acute in passenger travel because cars account for 79% of all travel annually in the European Union and 87% in the USA. Nearly one third of vehicles on the road are heavy goods vehicles and buses.

As a result, road transport causes the most severe social, environmental and economic consequences. Road transport causes over 95% of accidents and 90% of road deaths. The fatality rates of water, air and rail transport are clearly lower than those of road transport [1]. While Europe boasts an accident fatality rate half that of Asia, Poland is sadly No. 1 in Europe and No. 20 in the world for its road deaths [2].

Several factors affect how safely drivers perform in road traffic. They can be grouped into organizational (length of route, travel time, rest breaks), workplace (ergonomics, physical factors in the driver's cab, physical condition of the vehicle), external (quality of road and markings, traffic volume, weather, time of day) and personal (physical and mental fitness, personality, age, health, sleep deficit, fatigue) factors.

Performance changes during the day. It increases one hour after awakening to reach its maximum in the afternoon. It drops significantly in the evening and hits its minimum at night (2:00–3:00). The biological clock adjusts life processes to daytime activity and night-time rest. Working at night usually involves problems with sleeping, mood swings, reduced alertness, poorer visual and motor co-ordination and disorders [3].

Consequently, sleep restriction, driver fatigue and falling asleep at the wheel are some of the key factors contributing to road accidents. As we know from research, driver fatigue causes 1%–3% of road transport accidents with up to 20% of those accidents occurring on major roads and motorways. Researchers agree that accidents

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caused by driver fatigue are significantly underreported due to unclear criteria [4].

The question should be whether driver fatigue, especially involving truck drivers in transit through Poland, is an important factor of Poland's road safety. If so, when and where is the problem most acute and how can it be mitigated? Finding the answers to these questions is the main purpose of this article.

2. DRIVER FATIGUE

2.1. Problem

Fatigue is usually defined as an internal condition leading to a reduced ability to perform as a result of previous exertion. In the case of driver fatigue, an extended definition includes sleepiness, drowsiness, micronaps, reduced attention span and motivation to act, reduced alertness, changes in performance and propensity to make mistakes. Sleepiness and drowsiness can result from fatigue or the urge to sleep at night.

Driver fatigue results from road traffic activity in an environment of five basic elements: driver, vehicle, road traffic, road and its environment. Because of the complexity of the driver's situation, fatigue can be divided into the following types [5]:

- muscular (physical) fatigue caused by static load and forced posture while driving;
- sensory fatigue leading to a reduced response of the senses as a result of long-term exposure to specific stimuli (light, sound, etc.);
- mental fatigue involving reduced cognitive capacity as a result of a shorter attention span and the monotony of driving (long trips, monotonous road environment, night-time, etc.);
- emotional fatigue as a response to stress (time pressure, conflicts with passengers, etc.).

Fatigue is directly influenced by the type of work, time of waking up and time of day when the driver is working [4]. Driver fatigue is a contributing factor to reduced cognitive capacity (lower threshold of perception, poorer memory, poorer motor capacity) causing the driver to make unintentional mistakes (e.g., running a red light, failing to yield). These mistakes can cause accidents [6]. There are other, more important, contributing factors: gender, age, social and economic status, type of vehicle, annual kilometres travelled, speed and type of road. This article will focus on the type of vehicle, driver personality and behaviour, working hours, frequency of driving and kilometres travelled, and road-related factors. It will also look at ways to reduce the number of fatigue-related accidents.

Sleepiness and fatigue, especially when caused by long working hours and sleep restriction (causing reduced alertness, poor concentration on the road and road environment, or distraction), are the main risk factors of accidents involving truck drivers. The effects of these factors can be seen in the likelihood of a fatal accident [7]. Most accidents caused by professional drivers happen at night [8].

Fatigue goes hand in hand with the need to sleep (sleepiness); it can also be influenced by other factors such as pressure on the drivers or the condition they are in (e.g., illness, emotional state), which could impair their ability to perform. Friswell and Williamson showed that 38% of drivers of short-haul light vehicles (under 2 tonnes of gross vehicle weight, up to 100-km range from the base) felt tired at least once a week and 45% had fallen asleep at the wheel within the past 12 months [9]. Most drivers who felt fatigue while driving admitted to poorer performance with slower reaction time, a drop in alertness and attention. Fatigue tends to affect people working in a rush, with long commutes, working long hours daily and weekly, and doing unpaid overtime.

There is a strong relationship between age and fatigue (with older drivers more susceptible to fatigue) and between gender and fatigue (women are much less susceptible to fatigue but this can be influenced by factors unrelated to work). Social and economic status is another contributing factor. Workers with a low social status are affected by fatigue faster when working long hours compared to those with a higher status. The latter experience fatigue when exposed to heavy workloads and stress. Those commuting (in the case of long commutes) sleep less and tire during the day; people who are more active in the evening and people who are more active in the morning tire at different times. The type and personality of workers can predispose them to, e.g., falling asleep at the wheel [10]. Medical conditions and important life events increase the risk of a road accident (in connection with the medical condition or life event) [11].

Young drivers (aged 18–22) are part of the high-risk group because of their lack of experience or knowledge how to handle fatigue, failure to understand potential threats or overestimating their ability to drive. There is a strong link between the frequency of night-time driving and the perception of risk of a fatigue-related accident. Novice drivers fear such accidents more than drivers who often drive at night. In addition, most more experienced drivers said that they would continue driving when feeling fatigue and would try to fight it. Those with less experience said they would discontinue driving [12].

A comparison of how long drivers had slept before an accident and the time of the accident showed that they had slept less than usual. In addition, when they sleep significantly less than usual, the risk of a critical event increases. This suggests that fatigue can play a major role [13].

Lack of sleep in 17 h or longer deteriorates driving performance to a level comparable to drink driving with a blood alcohol concentration of 0.5, a factor which increases the risk of an accident [14].

Professional drivers can handle sleep restrictions much better than other road users. However, among those aged 50 and over, truck drivers, especially those driving without seatbelts on, are more likely to be killed in an accident [7].

When sleep is restricted, the driver suffers sleep attacks, a possible cause of run-off-the-road accidents. Philip, Sagaspe, Moore, et al. showed that sleep deficit increased the risk of lane departure over eight times compared to a driver who had had a good night's sleep. Sleep deficit also depended on the number of kilometres driven annually and the drivers' age. Poorer driving performance had to do with sleepiness not fatigue. Sleepiness combined with fatigue made reaction time longer [14].

Physical exercise (regular and intensive irregular exercise) has a positive effect on the quality and quantity of sleep. Drivers doing less exercise tire more, while regular exercise increases vigour, alertness and reduces fatigue as long as the exercise is not too intensive (it can cause physical fatigue of the body). Exercise also has a positive effect on alertness and response time at the wheel, which translates into a lower risk of an accident [15].

Annual kilometres travelled is a very important factor contributing to accidents. The likelihood of becoming involved in a traffic accident increases with the distance travelled [11, 16]. The risk of a road accident depends on the kilometres travelled and the drivers' age. For those who drive a lot, the risk of being involved in an accident decreases with the number of kilometres they drive annually and their age and for those who drive very little (<3000 km/year) that same risk decreases until they are 60 to rapidly increase as they grow older [17].

The factors that affect driving performance are divided into internal factors influencing the driver's physical and mental state (i.e., daily variations in working time, time spent driving, sleep disorders), and external ones (e.g., road geometry, repetitive patterns and a monotonous environment). Internal and external factors are interrelated and affect alertness, vigilance and information processing. When combined, they cause fatigue Thiffault and Bergeron defined as a state which decreased the ability to drive due to a change in alertness and attention. There is a relationship between the monotony of the road and fatigue. Because a monotonous road offers no stimuli, alertness and vigilance decrease, boredom increases and driving becomes "routine". A drop in alertness deteriorates information processing and the quality of driving performance due to inattention. Boredom and reluctant driving cause drivers to shift their attention from driving to other activities, which leads to fatigue. Consequently, when driving in a monotonous road environment, drivers tended to show more frequent and intensive steering movements, generating higher levels of fatigue and a drop in alertness [18].

When driving is monotonous (e.g., on a motorway or a road with slow traffic), young professional drivers (aged 20–30) are more sleepy and less alert than middle-aged drivers, i.e., they are more likely to fall asleep and are more frequently involved in sleepiness-related road accidents, especially at night [14].

Young professional drivers experience a significant drop in alertness compared to middle-aged drivers, especially when traffic volumes are low. They also experience a strong urge to sleep in the evening [19].

The literature primarily addresses the problem of individual drivers, factors affecting fatigue and the effects of fatigue on accidents. There is less emphasis on the location of accidents and the road factors causing fatigue-related accidents. The objective of this work is to use the relative risk factor to understand how the time of day affects the consequences of fatigue-related accidents and to present a tool for identifying relevant high-risk sites.

2.2. Method

Road safety can be managed like any other component of a quality system. When the system is first developed, the level of risk (targeted or acceptable) is defined and then maintained or reduced when the system is operated. Three groups of measures are used to analyse and assess risk on a road network [2]:

- individual risk (i.e., the behaviour of a single road user on a road network or a single road);
- group risk (i.e., the behaviour of a group of road users on a specific road);
- societal risk (i.e., the behaviour of entire social groups in a specific area, e.g., a country, region or city).

People take a strong interest in their own risk as individual road users. Individual risk in this article

- in the operational approach means the probability of a consequence of a specific severity during one trip or within a specified time when the road user is exposed to a risk caused by road infrastructure and other vehicles;
- in the strategic approach means the level of intensity of a specific category of consequences (injury or economic consequences) versus the distance travelled in a unit of time.

The individual risk of a single road user is an important idea in understanding the role of road infrastructure and road user behaviour as a factor contributing to traffic risk [20]. Individual risk in the strategic approach refers to the average behaviour of a country's population and defines the average probability with which a member of the community may suffer consequences per one unit of kilometres travelled in a specific area and period. If known, it helps road authorities to manage roads at specific levels of risk depending on the type of road and traffic. Individual risk can be controlled and effectively reduced. We use this risk to identify possible improvements and the targeted level of risk on a specific road.

To assess operational risk, we used the relevant risk rate, i.e., the relation between a specific value of a selected risk measure and a baseline value. Equation 1 calculates that measure:

$$RR = \frac{R_a}{R_b}, \tag{1}$$

where RR = relative risk rate; R_a = existing risk (e.g., no treatment provided): the condition before; R_b = baseline risk (e.g., treatment provided): the condition after.

Equation 1 expresses the general model of strategic individual risk [2]:

$$RI = CAC_{(H)} = \frac{NAC_{(H)}}{VTK_{(H)}}, \tag{2}$$

where RI = individual risk; $CAC_{(H)}$ = concentration of accidents or casualties (injuries + fatalities) per 1 billion vehicle kilometres in clock time H; $NAC_{(H)}$ = number of accidents or casualties (injuries + fatalities) in clock time H; $VTK_{(H)}$ = vehicle kilometres travelled (billions of vehicle kilometres per year) in clock time H.

The measures of risk were used to develop a model for determining the level of risk drivers are exposed to depending on the time of day and to classify road sections in relation to the risk of fatigue-related accidents on Poland's national roads.

3. ANALYSIS

3.1. Subject of Analysis

With an area of 312 000 km^2, Poland is populated by 38.1 million people. The country has 382 000 km of roads, of which 68% are paved roads and 0.3% are motorways and express roads. The network is used by over 21 million vehicles, of which 74% are passenger cars and 20.8% are heavy goods vehicles. Poland's motorization rate is 550 vehicles per 1000 population.

In 2009, in Poland there were 44 200 road accidents (with casualties) with 56 000 people injured and 4572 people killed. The number of fatalities is the rate used for comparisons with other countries. The number of accidents (casualty accidents) and the number of injuries are below the actual figures. This is so because of the injury and road accident definitions used by Polish police. The KABCO injury rating scale (widely used in the USA and in other countries) is a 5-point scale which consists of categories designated *fatal* (K), *serious* (A), *moderate* (B), *minor* (C), and *none* (O) [21].

When compared, the classification of personal injury in Poland and on the KABCO injury rating scale [21] shows that in fact Poland does not use one of the injury groups, i.e., *minor* injury (C on the KABCO scale). The level of injury considered as slight in Poland falls under *moderate* (category B) on the KABCO scale. Poland has a relatively low injury severity rate compared to other countries (25%–60% in Switzerland, Germany, Sweden and the United Kingdom) but its fatality rate is 2–2.5 times higher than in those countries. This suggests that Poland's injury accidents are underreported because slight injury accidents are considered minor crashes or are disregarded at all. As a result, the number of injuries and accidents cannot be reliably compared between Poland and other countries; the conclusions formulated here are based on fatal accidents [22].

The primary road network is made up of national roads, which are ~18 000 km long (6.9% of all paved roads) including ~5000 km of international roads. National roads carry the main transit international, national and inter-regional traffic and ~30% of overall traffic. In terms of the vehicles using these roads, 70.3% are passenger vehicles and 29.3% are trucks, buses and tractors.

3.2. Accidents

The analysis covers 5 years (2003–2007). Within this period, there were 246 700 road accidents (casualty accidents) with 27 600 people killed and 266 800 people injured. Drivers caused 80.5% of accidents involving 74.2% of all fatalities and 85.5% of injuries [23].

Police records show that accidents caused by driver fatigue or falling asleep at the wheel accounted for 1% of all accidents and 3.7% of all road deaths and 1.2% of all injuries. This apparently low rate of driver fatigue accidents [4] is the result of a different method for recording accidents in Poland because police officers at the scene are required to name what they think is the single most important cause of the accident.

Over 60% of accidents caused by driver fatigue occurred on national roads. For this reason, the analysis will focus on accidents (casualty accidents) which happened on national roads in 2003–2007.

In 2003–2007, driver fatigue and sleepiness caused 1685 accidents on Poland's national roads; 2708 people were injured, 418 were people killed. Table 1 shows that these accidents and casualties have been systematically growing in consecutive years. Fatigue or sleepiness accidents recorded by the police on national roads accounted for 3.2% of all accidents with 5% of all fatalities and 3.4% of all injuries. This makes them the number 5 cause of accidents on national roads.

TABLE 1. Number of Accidents and Casualties Caused by Driver Fatigue or Driver Falling Asleep at the Wheel on Poland's National Roads in 2003–2007

Year	Accidents	Casualties	
		Injuries	Fatalities
2003	278	442	72
2004	301	501	78
2005	328	502	84
2006	404	673	95
2007	378	590	89
total	1685	2708	418

Driver fatigue can lead directly to incidents, collisions or road accidents. If arranged in the shape of a pyramid, road accidents would be at its top. Table 2 lists the most frequent road accidents in which driver fatigue was the main cause:

- hitting an obstacle (tree, light pole, bridge head, etc.) next to the road following running off the road;
- head-on collisions following lane departure;
- rollover following loss of vehicle stability;
- rear-end or side impact following failure to brake or when bypassing other vehicles.

Accident severity is highest in the case of head-on collisions (Table 3).

3.3. Causes and Circumstances

The study looked at the time and location of accidents. Their time can be presented by year, week or day. In a year, accidents and casualties are most frequent (40%–42%) in the three summer months of June, July and August (Figure 1). This is due to longer travel time on longer days and a higher number of tourist and weekend trips. During the week, most accidents and casualties (46%–49%) occur on the three consecutive days of Friday, Saturday and Sunday. This has to do with driver fatigue towards the end of the week and longer trips over the weekend.

During the day, most accidents and casualties (50%–54%) occur in daytime but given the fact that daytime traffic accounts for over 70% of all traffic, night-time accidents should be considered as well. Figure 2 shows the distribution of fatigue-related road accidents and casualties on national roads by hour of the day in 2003–2007. As you can see, the highest number of driver fatigue accidents and casualties occurs in the first 8 h of the day, with 61% of accidents and injuries and 69% of fatalities. One of the reasons for this is that this time of day is a rest period.

Three layers are considered in this article to identify the location of driver fatigue accidents: region, road division and road elements. Accident location data is essential for traffic enforcement services (road transport inspection and the police) to ensure proper deployment. It is also essential

TABLE 2. Number of Accidents and Casualties by Type of Fatigue-Related Accident on Poland's National Roads in 2003–2007

Type of Accident	Accidents	Casualties	
		Injuries	Fatalities
Hitting a tree	608	849	128
Head-on collision	348	659	171
Rollover	263	467	28
Rear-end collision	219	345	55
Side impact	119	186	25
Other	128	202	11
total	1685	2708	418

TABLE 3. Accident Severity Expressed with Casualties per 100 Accidents by Type of Fatigue-Related Accident on Poland's National Roads in 2003–2007

Type of Accident	Casualties (per 100 Accidents)	
	Injuries	Fatalities
Hitting a tree	139.6	21.1
Head-on collision	189.4	49.1
Rollover	177.6	10.6
Rear-end collision	157.5	25.1
Side impact	156.3	21.0
Others	157.8	8.6
average	160.7	24.8

for road authorities when organizing and building car parks and service areas.

Poland is divided into 16 regions. Studies have shown that accident numbers differ significantly from region to region. The highest number of fatigue-related accidents and casualties is recorded in northern, western, southwestern, southern, southeastern and central Poland. The share of these casualties in overall casualties on national roads is 1.5%–7.3% and it is highest in the north, northwest, west, south and southeast. It is important to note that major transit routes going east–west and north–south across Europe cut across those regions.

Road accidents caused by driver fatigue are usually recorded on single carriageways with lanes in each direction (86% of all accidents), on straight sections (81% of accidents) and horizontal bends (12% of accidents). Driver fatigue accidents are most frequent on motorways with 13.2% of all accidents and 13.5% of all casualties on national roads, which is almost four times more than on the other types of roads. The possible causes can include monotony and higher speeds when driving on motorways. As a result, the consequences of falling asleep at the wheel or making a fatigue-related mistake are more severe.

The network of national roads constitutes the backbone of the Polish road network and comprises ~100 road divisions. Most fatigue accidents occurred on motorways A2, A1 and A4 (over 10%) and on roads 2, 3, 17, 18 and 22 (over 5%).

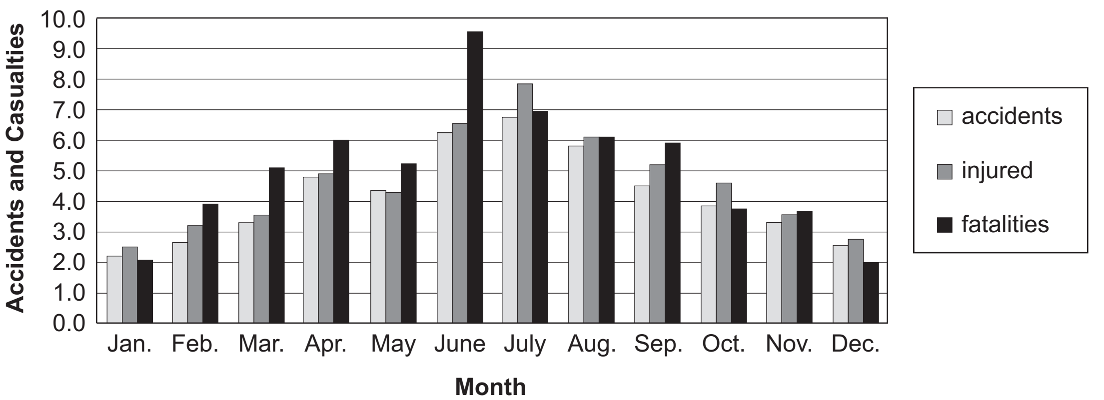

Figure 1. Distribution of fatigue-related road accidents and casualties (injuries + fatalities) on Poland's national roads by month in 2003–2007.

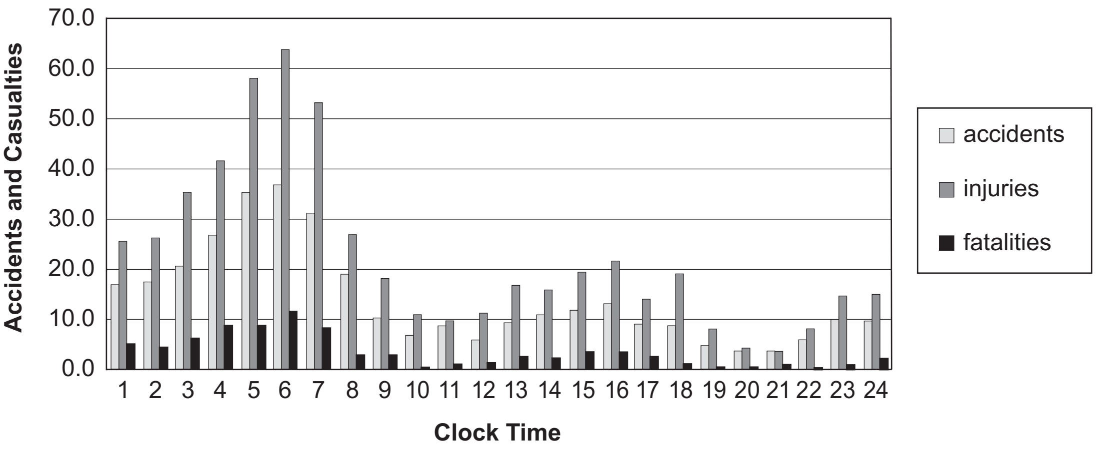

Figure 2. Distribution of the average number of fatigue-related road accidents and casualties (injuries + fatalities) on Poland's national roads (per year) by hour of the day in 2003–2007.

3.4. Accidents and Casualties

The accidents in question are caused mainly by drivers. The important contributing factors include the age and gender of the driver and the type of vehicle. A study conducted in 2005–2007 examined the percentage share of three groups of drivers in overall drivers. The results were as follows: young drivers (aged 25 and under) at 13%, mature drivers (aged 25–60) at 81%, older drivers (aged 60 and over) at 6% [24]. Those aged 20–35 caused 48% of accidents with 48% of injuries and 42% of fatalities in this type of accidents. In the context of age groups, those aged 30–60 cause 3.5%–4% of all fatigue accidents with 3.5%–4.5% of all injuries and 5.5%–10% of fatalities.

Drivers of passenger cars caused 72.4% of driver fatigue accidents with 72% of injuries and 65% of fatalities. Truck drivers caused 26.5% of fatigue-related accidents involving 25.3% of injuries and 34% of fatalities.

The casualties of these accidents are drivers, passengers and pedestrians. The age of the casualty is an important factor. Road users aged 20–30 account for 30% of casualties and road users aged 20–50 account for as high as 70% of all accidents involving fatigue. Among casualties, drivers make up 47.5% of injuries and 59.6% of fatalities while car occupants make up 51.9% of injuries and 38.9% of fatalities. The casualties include pedestrians (0.6% of injuries and 1.4% of fatalities).

4. TIME OF DAY AND ACCIDENT RISK

A 2005 general survey carried out on national roads in Poland [25] and the results of a number of our own studies on daily traffic distribution [24] helped to estimate kilometres travelled on Poland's national roads broken down by year and time of day. Figure 4 shows the distribution of aggregate kilometres travelled in hourly breakdown on national roads in 2005. As can be seen from the chart from 23:00 to 6:00 total kilometres travelled on Poland's national roads are under 1 billion vehicle kilometres per hour, but from 8:00 to 20:00 the number is over 2 billion vehicle kilometres per hour.

The number of fatigue-related accidents and casualties broken down by annual and hourly periods was determined with the SEWIK database. Figure 2 shows the aggregate number of fatigue-related accidents, injuries and fatalities in 2003–2005 on national roads. Equation 1 was used to compute the concentration of accidents, injuries and fatalities on Poland's national roads by year and time of day. Figure 5 is a chart of the average concentration of fatigue-related accidents and casualties in 2003–2007.

Figure 5 shows that from 9:00 to 22:00 the concentration of accidents and casualties is relatively low, it increases sharply from 22:00 to 3:00, only to drop significantly from 6:00 to 9:00. As a

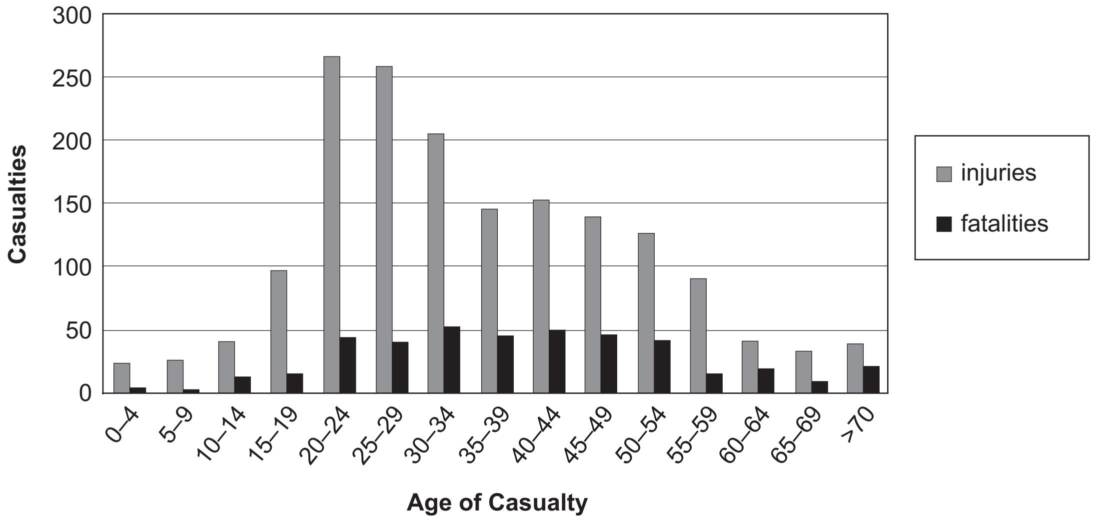

Figure 3. Distribution of the number of casualties (injuries + fatalities) in fatigue-related accidents on national roads (per 5 years) by age of casualties in 2003–2007.

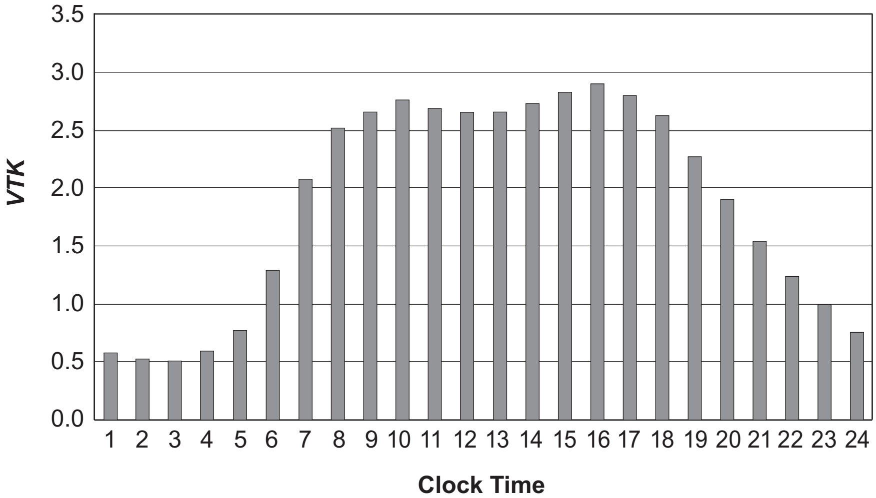

Figure 4. Distribution of vehicle kilometres travelled on Poland's national roads in 2005 by clock time. *Notes. VTK* = billions of vehicle kilometres per year.

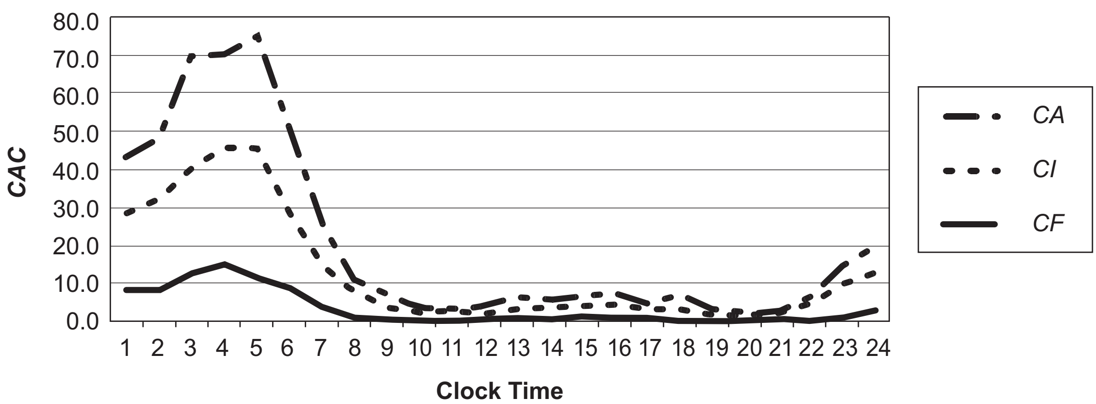

Figure 5. Distribution of the average concentration of fatigue-related accidents and casualties on Poland's national roads in 2003–2007 by clock time. *Notes. CAC* = concentration of accidents or casualties (injuries + fatalities) per 1 billion vehicle kilometres, *CA* = concentration of road accidents (accidents per 1 billion vehicle kilometres), *CI* = concentration of injuries (injuries per 1 billion vehicle kilometres), *CF* = concentration of fatalities (fatalities per 1 billion vehicle kilometres).

result, the concentration of accidents and casualties is highest from 3:00 to 6:00.

The data were used to develop a model for estimating the concentration of accidents and casualties depending on the time of day. To ensure that the model is easily understood, two time scales were introduced: computational time T and clock time H. The relationship between them is as follows:

$$T = \begin{Bmatrix} H - 21\text{h}, \text{ for } H = 22{:}00-24{:}00 \\ H + 3\text{h}, \text{ for } H = 1{:}00-21{:}00 \end{Bmatrix}. \quad (3)$$

A power-exponential function describes the model for the concentration of accidents and casualties (Equation 4):

$$CAC_{(T)} = \beta_0 + T^{\beta_1} \cdot \exp\left(-\beta_2 \cdot T - \beta_3\right), \quad (4)$$

with

$$\beta_0 \cong ACAC_{9-21}, \quad (5)$$

where $CAC_{(T)}$ = concentration of accidents or casualties (injuries + fatalities) per 1 billion vehicle kilometres in computational hour T; β_0, β_1, β_2, β_3 = equation coefficients; $ACAC_{9-21}$ = average concentration of accidents or casualties (injuries + fatalities) from 9:00 to 21:00 in clock time (accidents or casualties per 1 billion vehicle kilometres). Table 4 shows the parameters of Equation 3 for the concentration of accidents and casualties computed with STATISTICA version 10.

TABLE 4. Parameters From Equation 4 for the Concentration of Accidents and Casualties (Injuries + Fatalities) of Fatigue-Related Accidents on Poland's National Roads ($p < .001$)

Measure of Risk	β_0	β_1	β_2	β_3	R^2
CA	3.115	8.513	1.354	3.518	.877
CI	5.001	9.265	1.433	3.775	.851
CF	0.539	9.477	1.489	5.450	.732

Notes. β_0, β_1, β_2, β_3 = equation coefficients; *CA* = concentration of road accidents (accidents per 1 billion vehicle kilometres), *CI* = concentration of injuries (injuries per 1 billion vehicle kilometres), *CF* = concentration of fatalities (fatalities per 1 billion vehicle kilometres).

Figure 6 shows the relationships between the concentration of accidents and casualties and the time of day on Poland's national roads based on the models described with Equation 3. As can be seen from the chart the concentration of fatigue-related accidents and casualties on Poland's national roads is highest from 3:00 to 16:00 and lowest from 9:00 to 22:00. While the model is helpful with explaining the time of these accidents, it cannot be used for forecasts. A forecast model would need a bigger number of independent variables (e.g., kilometres travelled, type of road).

An analysis of the results (Figures 2, 5 and 6) shows strong disproportions between the risk of becoming involved in a road accident caused by fatigue during the day and night. To quantify this relationship relative risk was computed with Equation 6:

$$RRAC_{(T)} = \frac{CAC_{(T)}}{ACAC_{9-22}}, \tag{6}$$

where $RRAC_{(T)}$ = relative risk of being involved in a fatigue-related accident or being a casualty as a result of a fatigue-related accident on Poland's national roads in computational hour T; $CAC_{(T)}$ = concentration of accidents or casualties (injuries + fatalities) per 1 billion vehicle kilometres in computational hour T; $ACAC_{9-22}$ = average concentration of accidents and/or casualties (injuries + fatalities) from 9:00 to 22:00 in clock time (accidents or casualties per 1 billion vehicle kilometres).

Equation 6 was used to calculate the relative risk of being involved, being injured or dying in an accident caused by fatigue or a driver falling asleep on Poland's national roads in computational hour T. Figure 7 shows the distribution of

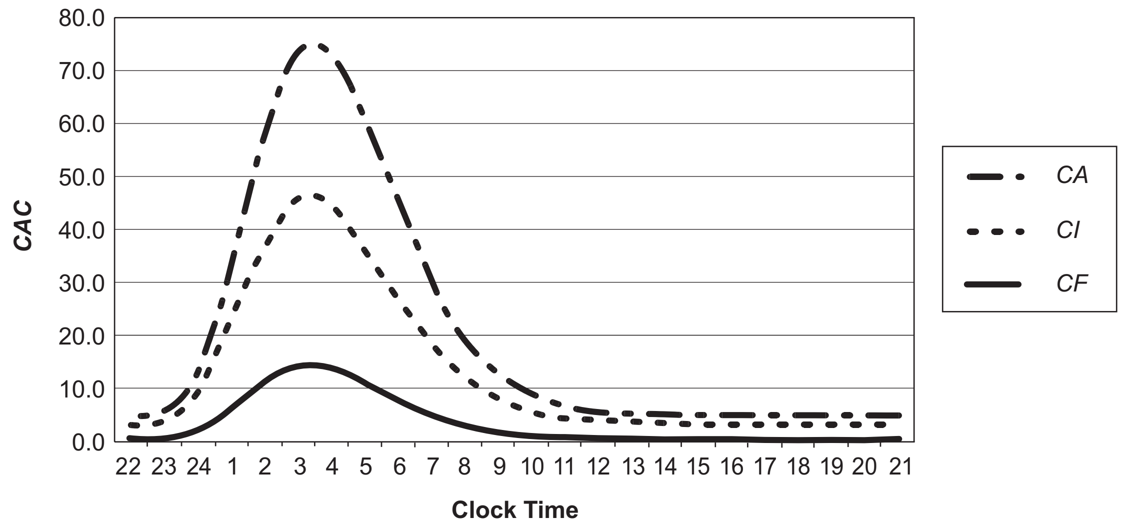

Figure 6. Distribution of the average concentration of fatigue-related accidents and casualties on Poland's national roads computed with Equation 3. *Notes. CAC* = concentration of accidents or casualties (injuries + fatalities) per 1 billion vehicle kilometres, *CA* = concentration of road accidents (accidents per 1 billion vehicle kilometres), *CI* = concentration of injuries (injuries per 1 billion vehicle kilometres), *CF* = concentration of fatalities (fatalities per 1 billion vehicle kilometres).

relative risk versus the average daily value (9:00–22:00).

Analysis of the results shows that the relative risk of fatigue-related accidents and casualties is

- 5 times higher from 23:00 to 8:00 than from 9:00 to 22:00;
- highest from 2:00 to 6:00, and when compared to the period from 9:00 to 22:00 it is
  - 13–15 times higher for accidents and casualties,
  - 21–28 times higher for fatalities.

The results show the seriousness of the problem of fatigue accidents at night. Contrary to popular opinion, night-time is not the safest time for long journeys.

5. CLASSIFICATION OF RISK

Similarly to EuroRAP methodology [20], a classification of sections of Poland's national roads was developed to map fatality and severe injury accidents using five classes of risk: high, medium-to-high, medium, low-to-medium and low. Figure 8

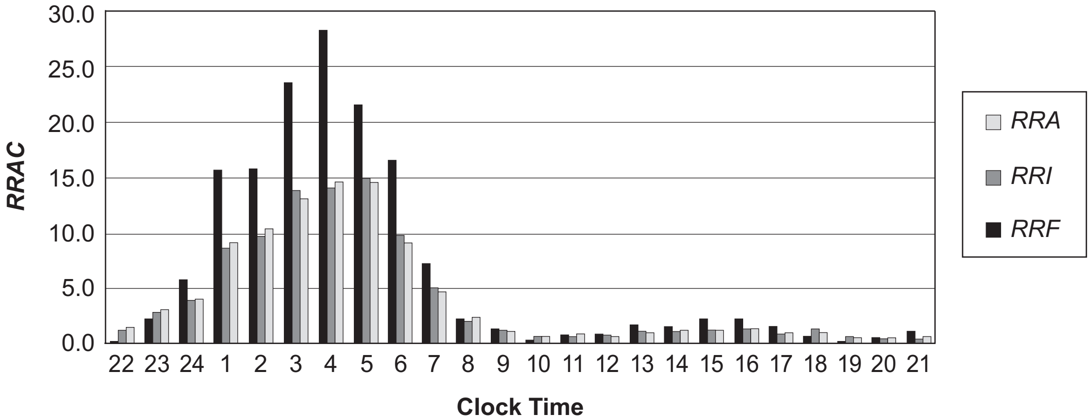

Figure 7. Distribution of the number of casualties in fatigue-related accidents on Poland's national roads by clock time in 2003–2007. *Notes. RRAC* = relative risk of being involved in a fatigue-related accident or being a casualty as a result of a fatigue-related accident, *RRA* = relative risk of being involved in an accident, *RRI* = relative risk of being injured, *RRF* = relative risk of dying.

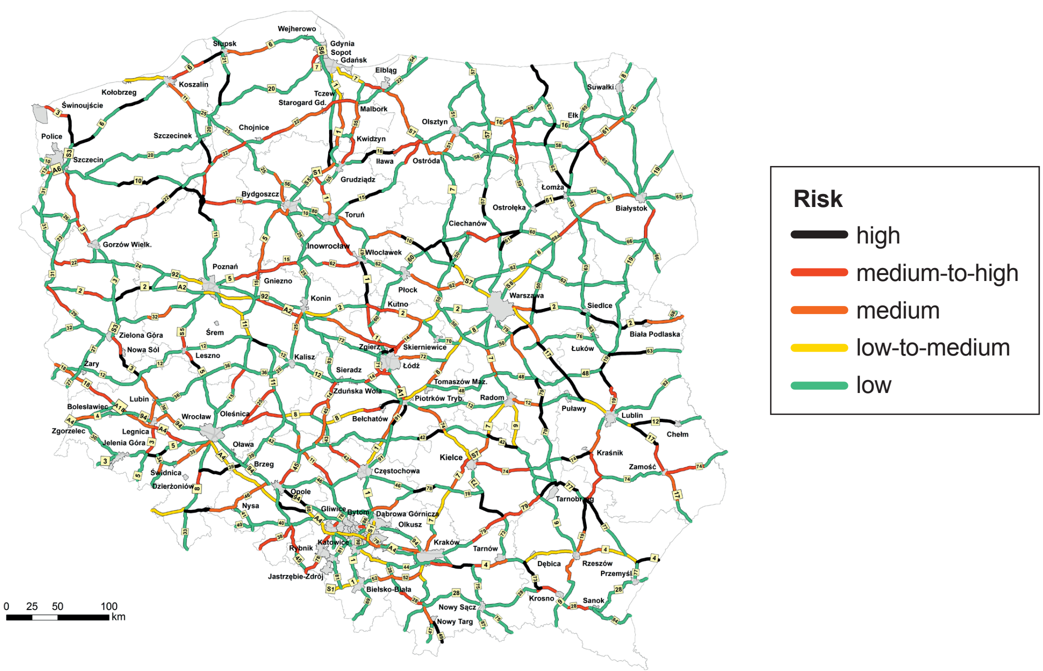

Figure 8. Map of accident risk caused by road-user fatigue on Poland's national roads in 2007–2009.

shows a map of the risk of fatigue-related accidents on Poland's national roads in 2007–2009.

As you can see from the map sections of medium-to-high and high risk of becoming involved in a fatality or severe injury accident caused by road-user fatigue occur on 23.5% of the length of national roads. These sections claimed 71.7% of fatalities and serious injuries.

Sections where risk caused by road-user fatigue is medium-to-high or high are mainly found on

- transit roads carrying traffic towards the borders with Lithuania (in the northeast), Ukraine (in the southeast), Germany (in the west);
- networks of tourist roads carrying traffic to the Baltic Sea;
- roads with poor geometry (e.g., roads 61 and 63); long, straight and monotonous sections (e.g., sections of road 17); sections of motorways (e.g., A1 in the north) following long sections of lower-class roads.

Knowledge of these facts can help national road authorities to reduce fatigue-related accidents and casualties by

- organizing and running campaigns addressed to drivers driving at night or driving long distances;
- designating and organizing vehicle check points (road transport inspection and the police);
- designating and organizing car parks, service areas and rest areas for drivers, especially along roads with predominantly long-haul traffic (transit and tourist traffic, etc.).

The map in Figure 8 will be helpful with this.

6. CONCLUSION

Fatigue and sleep deficit are a serious problem during night-time driving leading to reduced driving performance and eventually ending in a road accident. Fatigue-related accidents are more frequent on higher-class roads which carry transit traffic, especially trucks, tourist and inter-regional travel. The other contributing factors causing fatigue accidents on national roads in Poland are age of drivers, time of day, road geometry and roadside environment.

Night-time is the most dangerous time to drive on national roads in Poland. The risk of becoming a fatality in a fatigue accident is 28 higher during the worst period at night than during the day. The power-exponential model is helpful with describing the overall daily distribution of the concentration of fatigue-related accidents and casualties on Poland's national roads.

The risk map showing fatality and severe injury accidents will help national road authorities to take effective steps to reduce the risk of accidents caused by driver fatigue on the national roads in Poland.

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