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Seasonal Influences on Driver Behaviour: A Review of Car-Following Dynamics in Hot and Cold Climates

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ABSTRACT

This paper reviews the seasonal impacts on driver behaviour, focusing on car-following dynamics in adverse weather conditions, including snow, icy roads, glaring sunlight, and fog. Existing literature underscores the significant effects of these weather conditions on traffic flow, driving behaviour, and accident rates. In colder climates, snow and ice disrupt traffic, slow vehicle speeds, and increase accidents, particularly affecting passenger cars more than trucks, which typically operate on strict schedules. In warmer climates, sun glare impairs visibility, contributing to congestion and accidents. The paper synthesises findings from various studies, revealing key research gaps, including the differing behaviours of heavy trucks and passenger cars under extreme weather, the combined effects of multiple adverse weather conditions, and the role of road geometry and maintenance in shaping driver behaviour. This review highlights the need for further investigation to better understand these factors and their impact on road safety. Future research should focus on integrating real-world driving data and exploring advanced technologies such as AI and IoT to mitigate the negative effects of seasonal weather. Ultimately, this research aims to inform more effective traffic management strategies and improve road safety across diverse climates.

1. INTRODUCTION

Understanding how seasonal variations influence driver behaviour is essential for crafting efficient traffic management systems and enhancing global road safety. Different seasons change weather conditions, such as temperature, precipitation, and visibility, which can significantly impact driving patterns [1]. Despite the importance of this topic, there is a notable gap in the literature, particularly in comparative studies of driving behaviour across different seasons and climatic conditions. This review synthesises existing research on the influence of seasonal changes on car-following dynamics and driver performance.

Seasonal changes can profoundly affect various aspects of driving, including speed, headway, and driver aggressiveness. For example, high temperatures in the summer can lead to increased driver stress and fatigue, potentially resulting in more aggressive driving behaviours. In contrast, winter conditions, characterised by lower temperatures, snow, and ice, can lead to cautious driving patterns and increased headways [2]. Kehagia et al. [3] highlight the critical role of Road Safety Audits (RSA) in identifying infrastructure deficiencies and safety risks on Greek roads, with proposed measures grounded in behavioural studies. Similarly, Alruwaili and Xie [4] demonstrate how connected vehicle (CV) technologies can mitigate driver unawareness and traffic conflicts, particularly on horizontal curves, while accounting for the influence of weather conditions on safety outcomes. Likewise, Adeliyi et al. [5] examine road traffic accident severity using machine learning models, identifying key contributing factors such as casualties, weather, lighting conditions, and the number of vehicles involved, with the J48 pruned tree model outperforming other predictive approaches. Furthermore, Bal and Vleugel [6] address the environmental challenges posed by freight transport, exploring how substituting maritime transport with road and rail alternatives can reduce emissions without compromising logistics. Understanding these seasonal effects, drivers' behaviour, and road safety modelling techniques are essential for tailoring traffic regulations, enhancing road safety measures, and improving vehicle design to accommodate different weather conditions [7].

This review paper is essential for comprehensively understanding how environmental factors, such as weather conditions, influence driver behaviour across different seasons. By synthesising studies from various climatic regions, the paper highlights key patterns and differences in driving behaviour, offering valuable insights for developing targeted traffic management strategies, informing policy decisions, and improving infrastructure planning. Furthermore, this review identifies significant gaps in the current literature and suggests directions for future research, aiming to advance our understanding of how environmental factors shape driver behaviour and impact road safety and efficiency.

The primary aim of this review is to analyse and integrate existing research on the impact of seasonal variations on driver behaviour, particularly focusing on car-following dynamics. This paper identifies common trends, discrepancies, and research gaps by examining the interplay between seasonal factors and driver behaviour, providing a foundation for future investigations. Understanding these dynamics enables policymakers and traffic authorities to design more effective interventions, improving road safety and traffic flow year-round. Ultimately, this review aims to contribute to developing strategies that enhance road transportation systems' safety and efficiency in response to seasonal challenges. This comprehensive analysis will help identify areas for further research and guide efforts to address the impact of environmental conditions on driver behaviour.

2. METHODOLOGY

The methodology for this review paper was developed using a systematic approach to comprehensively gather, analyse, and synthesise existing research on seasonal influences on driver behaviour, particularly car-following dynamics in both hot and cold climates. The research process involved an extensive search of peer-reviewed literature across major scientific databases, including Scopus, IEEE Xplore, and Google Scholar. Keywords such as "driver behaviour," "seasonal influence," "car-following dynamics," "hot climates," and "cold climates" were strategically combined using Boolean operators to maximise the search results and capture relevant studies. This study considers specific extreme weather conditions, including snow, ice, sun glare, fog, and extreme heat, reflecting the diverse environmental factors influencing driving behaviour.

The selection criteria were carefully defined to include studies that focused on the impact of environmental conditions, "whether extremely hot or cold," on car-following behaviour, traffic volume, speed adjustments, and overall traffic flow. The review prioritised studies published within the last two decades to ensure that recent developments and trends in driver behaviour were captured, as advancements in technology and traffic management practices have significantly evolved during this period. Foundational studies published before this timeframe were excluded unless they offered critical theoretical insights, which were otherwise addressed through secondary citations.

After an initial screening of abstracts and titles, complete articles were assessed based on the established inclusion and exclusion criteria. Studies were included if they provided empirical data, substantial theoretical insights, or robust models on the effects of weather on driver behaviour. Exclusion criteria applied to studies that lacked relevance to seasonal influences were limited to simulations without empirical validation or focused exclusively on unrelated driving aspects. Biases in the literature search were minimised by diversifying databases, applying consistent search protocols, and involving multiple reviewers to cross-check the study selection process. The selected studies were then categorised based on the environmental conditions examined, their geographical focus, and the methodologies employed.

A narrative synthesis was conducted to identify recurring patterns, discrepancies, and gaps in the literature. This synthesis incorporated findings from studies conducted in diverse geographical regions and climatic contexts to provide a balanced perspective. Specific focus was placed on the variations in car-following behaviour between passenger vehicles and heavy trucks, the influence of combined weather conditions, and how road geometry and maintenance exacerbate or mitigate these effects. The review highlights the impact of extreme weather conditions on car-following dynamics and outlines targeted areas for future research to advance traffic management and road safety.

3. CAR FOLLOWING DYNAMICS AND ENVIRONMENTAL CONDITIONS

3.1 Overview of car-following dynamics

Road user errors significantly contribute to traffic accidents, often stemming from misperceptions, distractions, misjudgements of traffic flow and distance, improper overtaking or turning, running red lights, failing to yield, and following other vehicles too closely. Tailgating, a specific form of following too closely, is particularly dangerous as it significantly increases the risk of collisions. Factors such as drunk driving, speeding, and inadequate street lighting at night, combined with poor visibility, further amplify these risks. Specific driver characteristics, like being male, and road features like type and grade, also play a critical role in accident likelihood [8]. While human error is the leading cause of traffic accidents, other contributing factors include vehicle defects, road deficiencies, and adverse environmental conditions, although these are less significant. Table 1 illustrates the interrelationship between these factors, with human error being the primary cause of accidents in the UK [9]. Based on police reports from different countries, the influence of road users, vehicles, and road environments emerges as the dominant cause of accidents, as shown in Table 2. However, these studies often generalise findings, which may overlook nuanced behavioural variations across different driver demographics and specific roadway conditions.

Table 1. Contributing factors and their interaction in 2020 [9]

Contributing Factors to Road Accidents	Percentage (%)
The driver failed to observe carefully	38%
The driver misjudged the path or speed of another person	20%
The driver acted negligently, recklessly, or rushed	18%
Poor turn or manoeuvre	12%
Loss of control	11%
Slippery road (due to weather)	8%
Travelling too fast	6%
Exceeding speed limit	7%
Sudden breaking	5%
The pedestrian neglected to look properly	7%

Car-following behaviour, a core aspect of traffic flow theory, focuses on the interaction between consecutive vehicles. This behaviour is essential for maintaining safe distances and ensuring smooth traffic flow, particularly on high-speed, multi-lane highways. Key parameters that define car-following behaviour include headway, speed, and acceleration. Headway is crucial for traffic safety and efficiency, whether measured by time or distance. Drivers often modify their headway according to their sense of safety and comfort, which fluctuates depending on traffic conditions [10]. However, research in this field frequently depends on simulations or controlled settings, which might not accurately reflect real-world complexities like driver distractions or the presence of various vehicle types. Several models have been developed to simulate car-following behaviour, with empirical and mathematical models being the most prominent. Empirical models rely on observed data, while mathematical models use equations to represent the relationships between variables. For example, Puan [11] demonstrated that empirical models of car-following behaviour are based on drivers' preferred following distances, as shown in Eq. (1):

$$H=A_0+A_1V \quad (1)$$

where, H denotes the distance headway (m), V refers to the vehicle's speed (m/s), A_0 represents the length of the car (m), and A_1 denotes the reaction time of the driver (s) [11].

Table 2. Factors contributing to road accidents in different countries [12]

Country	The Main Cause of Accidents (%)			
	Road User Error	Vehicle Defects	Road and Environmental Deficiencies	Others
Afghanistan	74	17	9	-
Botswana	94	2	1	3
Cyprus	94	1	5	-
Ethiopia	81	5	-	14
India	80	7	1	12
Iran	64	16	20	-
Pakistan	91	4	5	-
Philippines	85	8	7	-
Malaysia	87	8	7	-
Zimbabwe	89	5	1	5
UK	95	5	18	-

However, Connolly et al. [13] developed a Route Evaluation by Vehicle Simulation (REVS) model based on a single-carriageway section of the road. This model assumes that the car-following distance remains constant regardless of speed and that all vehicles have the same lengths. Despite their utility, these models often oversimplify vehicle interactions by assuming uniform driver behaviour and road conditions, limiting their applicability to diverse real-world scenarios. The relationship between the car-following distance is described by Eq. (2) [13]:

$$H=L+10 \quad (2)$$

where, H refers to the headway measured from rear to rear, and L denotes the length of the vehicle [13].

Further studies, like Hunt's [14], proposed headway relationships for different vehicle types, such as cars and heavy goods vehicles (HGVs). Four car-following headway relationships were proposed [14]:

$$\text{Car succeeding car, } H_{CC}=2.124V-4.31 \quad (3)$$

$$\text{Car succeeding HGV, } H_{CH}=2.052V+1.156 \quad (4)$$

$$\text{HGV succeeding HGV, } H_{HH}=2.79V-3.997 \quad (5)$$

$$\text{HGV succeeding car, } H_{HC}=2.854V-8.15 \quad (6)$$

where, H is the measured distance from the forefront (m), V is the speed (m/s) [14].

H_{CC} refers to "Heavy Car Succeeding Car," a term used to describe the following of a heavier vehicle by a car in a traffic flow context.

H_{GV} stands for "Heavy Goods Vehicle," commonly used to refer to large vehicles such as trucks and lorries that transport goods.

H_{CH} denotes "Heavy Vehicles," a broader category encompassing various heavy-duty vehicles, including HGVs.

H_{HH} refers to "Heavy Hitter Haulage," a term sometimes used in freight transportation to describe particularly large and heavy cargo vehicles.

H_{HC} stands for "Heavy Hill Hold Control," a term used to describe a control mechanism or system designed to manage the behaviour of heavy vehicles when driving uphill, particularly to prevent rolling back or losing control.

Chen et al. [15] applied linear regression analysis to evaluate how road type and weather conditions affect perceived risk levels. Their findings revealed that various factors significantly impact the perceived risk index (PRI), with basic road segments and clear skies as reference points, represented by the constant with an impact value of zero. The results were validated by a high R-square value and a residual plot, which showed an unbiased and homoscedastic distribution. While regression models have effectively captured the relationship between headway (the distance between vehicles) and vehicle speed, the models used in prior research do not apply to this study. This is because previous observations were limited to two-lane single-carriageway roads and intersections, making them unsuitable for the current context.

In contrast, traffic flow theory is pivotal in understanding car-following behaviour by evaluating parameters such as traffic density, mean speed, and flow rate. These measurable parameters can be assessed using a variety of formulae. Immers and Logghe [16] employed a microscopic approach to analyse traffic flow, focusing on the trajectory of each vehicle as it moves within a lane. The vehicle's position over time defines the trajectory, with its rear bumper as the reference point. Figure 1 illustrates the outcomes of an experiment that applied car-following models. In this experiment, two vehicles started from a stationary position, with the trailing vehicle maintaining a 100-meter distance behind the lead vehicle. The model assumes a reaction time of one second and a sensitivity parameter of 5000 m^2/s. Immers and Logghe [16] highlighted that these parameters are essential for understanding how the trailing vehicle responds to the lead vehicle's acceleration and deceleration. Their model effectively captures the dynamics of car-following behaviour, emphasising the critical role of reaction time and sensitivity in maintaining safe and efficient vehicle spacing within traffic flow.

Meanwhile, the impact of external environmental factors, particularly weather parameters, concerning traffic theory in studying driver behaviour is an area of research that has yet to be sufficiently explored. Rakha et al. [17] investigated the effect of inclement weather on the traffic stream behaviour on freeways regarding visibility and precipitation. Adverse weather was found to reduce operating traffic mean speeds, and the mobility and safety of drivers can be significantly impacted by reduced visibility caused by fog and rain. Furthermore, these models often overlook the combined impact of various environmental factors, including weather, road design, and traffic congestion, which can significantly alter driver perception, decision-making, and overall behaviour. This limitation underscores the need for more comprehensive models that integrate these factors to better understand driver behaviour under varying and complex conditions.

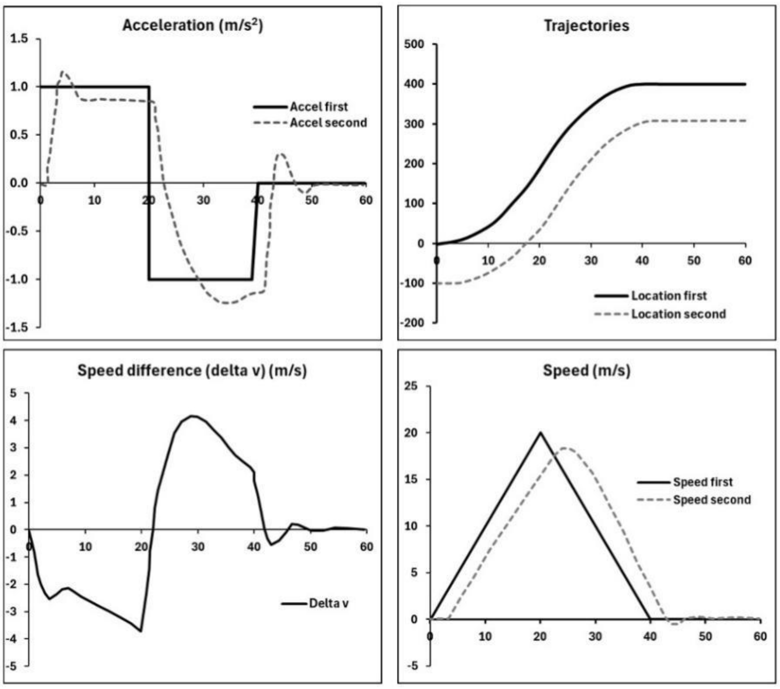

Figure 1. Car-following model simulation results [16]

3.2 Impact of environmental conditions on driver behaviour

Weather conditions such as temperature, wind, and snowfall notably impact motorists' travel patterns. As temperatures rise, the frequency of trips tends to increase, while colder temperatures and snowfall lead to fewer trips [18]. Rainy days are associated with higher traffic volumes and accident rates than sunny days. Hjelkrem and Ryeng [19] found that the risk to drivers increases by factors of 1.3, 1.5, and 2.5 on wet, muddy, and snowy road surfaces, respectively. Figure 2 highlights how weather factors like rainfall, temperature, wind speed, visibility, and humidity affect travel behaviour. These weather-induced changes in travel patterns often alter the use of transportation systems, leading to increases or decreases in road traffic, depending on the prevailing conditions.

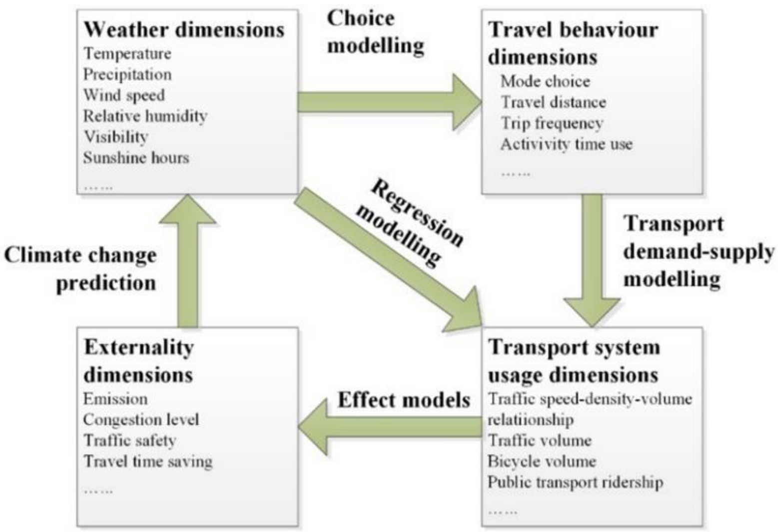

Figure 2. The interaction between weather conditions and travelling decisions [20]

Moreover, adverse weather conditions such as fog, dust storms, rainfall, and snow significantly impact driver behaviour and traffic safety. These conditions can severely impair visibility, alter road surface conditions, and affect vehicle handling, increasing the risk of traffic accidents. For example, fog and heavy rain can obscure a driver's view, making it difficult to judge distances and detect obstacles on the road [21]. Research shows drivers tend to increase their headways and reduce speeds during adverse weather to compensate for decreased visibility and longer stopping distances. However, these adjustments often fall short of fully mitigating the heightened risk of collisions, particularly rear-end crashes [22]. Rakha et al. [17] examined the effect of inclement weather on traffic flow on freeways, specifically focusing on visibility and precipitation. Their findings revealed that adverse weather conditions significantly reduce mean traffic speeds, underscoring the impact of weather on both traffic mobility and safety.

Tailgating, or following too closely behind another vehicle, becomes even more dangerous in adverse weather. Reduced visibility and slippery road surfaces significantly increase the stopping distance required to avoid collisions. Studies by Hamdar et al. [22] and Rawashdeh et al. [23] confirmed that adverse weather amplifies the risks associated with tailgating. In conditions like fog or rain, the likelihood of rear-end collisions increases due to delayed driver reactions and longer braking distances.

Additionally, Biswas et al. [24] highlighted the importance of maintaining appropriate headways, particularly in adverse weather conditions. Their study showed that tailgating contributes significantly to traffic accidents in Kuwait, stressing the need for public awareness and stricter enforcement of traffic regulations to prevent such behaviour. Environmental conditions are crucial in shaping driver behaviour, particularly within traffic flow theory. Adverse weather often forces drivers to adjust their speed and headway to maintain safety. The risks associated with these conditions can be mitigated through empirical research, mathematical modelling, and advanced technologies, ultimately enhancing overall traffic safety.

3.3 Seasonal variations in driving patterns

Seasonal variations play a significant role in influencing driving patterns and traffic flow. In regions with distinct seasons, drivers adjust their behaviour in response to changing weather, daylight hours, and road conditions. During the winter, conditions like shorter daylight hours, colder temperatures, and more precipitation, whether rain or snow, can significantly alter driving behaviours [25]. Drivers tend to adopt more cautious behaviour, including reducing speed and increasing headway to accommodate slippery road surfaces and decreased visibility [26]. In contrast, summer driving patterns are often more aggressive due to extended daylight hours and better road conditions. During this season, drivers are more likely to engage in risky behaviours such as speeding and tailgating, which increases the incidence of traffic violations and accidents [27]. This contrast underscores the importance of adaptive traffic management strategies tailored to seasonal changes.

For instance, Scandinavian countries, where harsh winters are common, have implemented traffic control measures such as mandatory use of snow tyres and dynamic speed limits that adjust to real-time road conditions. Similarly, traffic management systems in desert regions like the Middle East often incorporate heat-resistant road materials and weather alert systems to mitigate risks during extreme summer heat. These examples illustrate the critical role of localised strategies in addressing seasonal variations. Many studies have explored the impact of driver attitudes on traffic and accident rates. For example, Ma and Zhang [28] analysed how aggressive driving behaviours contribute to accidents at Highway-Rail crossings in the USA. They categorised drivers as aggressive if they engaged in risky actions such as "driving around or through the gate," "failing to stop," or "stopping on the crossing," based on data from the Federal Railroad Administration.

In contrast, drivers who "stopped and proceeded" were classified as calm. Their study found that aggressive drivers were linked to higher rates of injuries and fatalities at these crossings compared to calm drivers [28]. Such findings highlight the potential for targeted educational campaigns or stricter enforcement policies to address seasonal peaks in aggressive driving behaviours. Figure 3 illustrates the variation in driver behaviour across different weather conditions, showing that clear weather conditions increase the likelihood of aggressive driving, while adverse weather tends to curb such behaviours.

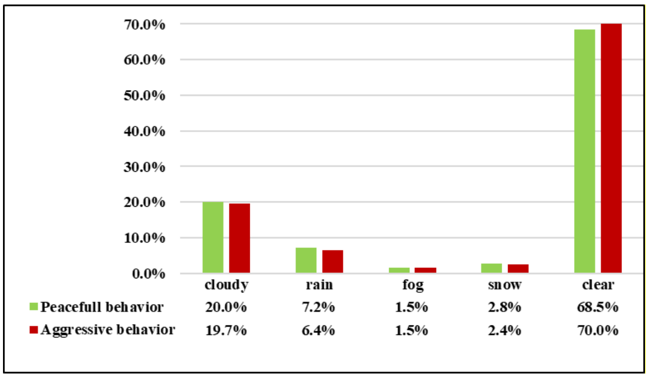

Figure 3. Weather influences drivers' behaviour [28]

Moreover, previous studies have extensively examined the influence of control variables on driver behaviour and traffic flow, focusing on the effects of weather conditions. When these variables are controlled for weather, they offer valuable insights into how different environmental scenarios impact traffic dynamics. For instance, Rämä and Kulmala [29] conducted a comprehensive study on the Finnish E18 motorway, where speed limit signs and variable message signs (VMS) were integrated with an automatic speed control system based on real-time meteorological data. This data was gathered from two unmanned road weather stations equipped with sensors that provided real-time information on road surface conditions. The study classified road and weather conditions into three categories: poor, moderate, and good, based on factors like rain intensity, snowfall, visibility, road surface condition, and wind velocity. The results showed that the weather-controlled VMS system positively impacted road safety, as it reduced mean traffic speeds and speed variations, indicating more consistent driving behaviour under changing weather conditions [29]. For example, in Finland, Rämä and Kulmala [29] studied the integration of VMS with real-time meteorological data on the Finnish E18 motorway. This system classified road and weather conditions into three categories: "poor, moderate, and good" based on factors like rain intensity, snowfall, visibility, road surface condition, and wind velocity. Their results demonstrated reduced mean traffic speeds and variations, contributing to more consistent and safer driving behaviour. Such adaptive systems, particularly in regions prone to sudden weather changes, can significantly improve road safety.

Similarly, Goodwin [30] reviewed research on the effects of weather on traffic flow, focusing on signalised arterial roadways. The study revealed that adverse weather conditions, such as rain and snow, increased driver headways, larger inter-vehicle spacing, and reduced speeds and acceleration rates. These changes in driving behaviour can significantly influence the efficiency of traffic signal timing plans, as modified driving patterns require adjustments to maintain smooth traffic flow. The findings highlight the need to consider weather conditions when designing and implementing traffic control systems. These findings are particularly relevant for regions with unpredictable weather, as they underscore the need for weather-responsive traffic signal timing plans. For instance, adaptive traffic signals that extend green light durations during heavy rain can help reduce congestion and ensure smoother traffic flow. Table 3 summarises various weather events and their effects on roadways and traffic operations, further demonstrating the complex interplay between weather and traffic flow [30].

Table 3. Impact of weather on roadways and traffic operations [30]

Weather Events	Impact on Roadways	Impact on Traffic Operations
Rain, snow, sleet, hail, flooding	▪ Reduced visibility ▪ Reduced pavement friction ▪ Lane obstruction and submersion ▪ Reduced vehicle performance ▪ Infrastructure damage	▪ Reduced roadway capacity ▪ Reduced speed and increased delay ▪ Increased speed variability ▪ Increased accident risk ▪ Road/bridge restriction and closure
High winds	▪ Reduced visibility due to blowing snow/dust. ▪ Lane obstruction due to wind-blown debris and drifting snow ▪ Reduced vehicle performance	▪ Increased delay ▪ Reduced traffic speed ▪ Road/bridge restrictions and closures
Fog, smog, and smoke	▪ Reduced visibility	▪ Reduced speed and increased delay ▪ Increased speed variability ▪ Increased accident risk ▪ Road/bridge restriction and closure
Lighting, extreme temperatures	▪ Infrastructure damage	▪ Traffic control device failure ▪ Loss of power/communication services

Future research could focus on the cost-benefit analysis of implementing advanced weather-controlled traffic systems in different regions to enhance the practical application of these findings further. Integrating real-time weather data into traffic management systems can help reduce the adverse effects of weather on driving behaviour and lower accident risks. In particular, regions with diverse seasonal climates, such as Scandinavia and desert environments, could serve as benchmarks for testing innovative strategies, offering valuable lessons for global implementation.

4. SEASONAL INFLUENCES ON DRIVER BEHAVIOUR

Previous literature has demonstrated that extreme weather conditions often lead to travel discomfort, manifested in slower speeds, delays or cancellations, adjustments during trips, and increased road accidents. Heavy snowfall and freezing temperatures pose significant travel hazards in regions with severe winter conditions, such as Canada and many northern locations. These adverse winter conditions frequently result in travel disruptions and trip adjustments, leading to noticeable variations in highway traffic patterns. For example, Roh et al. [26] found that during the winter season, traffic volumes on highways tend to fluctuate, with these variations depending on factors like the time of day, day of the week, highway location and type, and the severity of weather conditions.

Although previous studies have analysed total traffic volumes that include passenger cars and heavy vehicles, such as trucks, they have often lacked detailed information regarding the specific impact of winter weather on traffic across different terrains and geographies [25]. Moreover, these studies have not fully addressed the influence of winter weather on drivers' route selection, particularly for heavy vehicles. Crucially, none have investigated the potential for increased traffic on high-standard highways during poor weather conditions due to a shift from low-standard highways that lack adequate winter maintenance.

Many studies, however, have established a clear connection between traffic volume and weather conditions, highlighting how different weather events can cause significant fluctuations. Roh et al. [26] examined the effect of cold and snowy weather on traffic volumes on provincial highways in Alberta, Canada. Similarly, Datla et al. [31] studied traffic reductions on Iowa's interstate highways during winter storms, focusing on events with below-freezing temperatures, wet pavement, ongoing snowfall, and a minimum snowfall intensity of 0.51 cm/h. In another study, Keay and Simmonds [32] explored the relationship between weather and traffic on Melbourne's urban arterials, finding that traffic volumes decreased by 1.35% during winter and up to 3.43% during spring rainfall. Maze et al. [33] also reported significant traffic volume reductions on Interstate Highway 35 in Iowa during snowy days, with a 20% reduction on days with good visibility and low wind speeds, escalating to an 80% reduction when visibility dropped below a quarter-mile and wind speeds increased to 40 mph.

Although existing research exists, there is still a notable gap in understanding the effect of winter weather on truck traffic. Only a few studies have examined the interaction between snowfall, cold temperatures, and the traffic volumes of passenger cars and trucks, especially during extreme winter conditions. Additionally, previous studies have not explored the potential increase in traffic volumes on high-standard highways due to shifting traffic from poorly maintained low-standard highways during adverse weather. Roh et al. [34] found that car and truck traffic volumes respond differently to cold temperatures and snowfall. Cold temperatures had little impact on traffic volumes during no-snowfall days, but the interaction between cold and snow became more pronounced when snowfall increased. Passenger car volumes decreased more sharply than truck volumes during heavy snowfall, with very few cars on the road during snowfalls of 15 cm or more at temperatures of -20℃ or lower.

Furthermore, Roh et al. [35] highlighted that passenger cars face greater vulnerability to harsh weather conditions than trucks. This is likely due to the flexible schedules of passenger car drivers, who can delay, reroute, or cancel trips to avoid inclement weather. In contrast, trucks, often bound to mandatory schedules, must complete their journeys despite adverse weather, leading to different travel patterns. Interestingly, one study site revealed an increase in truck traffic during heavy snowfall, which contradicts findings from other studies. This suggests a shift in traffic from secondary to primary highways due to insufficient winter maintenance on lower-standard roads. This phenomenon indicates that, under certain conditions, traffic volumes on high-standard highways may increase during adverse weather due to traffic redirection from less maintained roads. Further investigation is required to understand this unique behaviour [35].

Adverse weather conditions significantly impact traffic operations and road safety, particularly reduced visibility caused by fog, rain, or snow. Poor visibility can increase travel time by up to 12%, a key factor in traffic accidents. The Federal Highway Administration reports that approximately 1,259,000 crashes occur annually due to adverse weather, with 28,500 incidents specifically linked to fog-related visibility issues. Another significant factor contributing to reduced driving performance is glare, which occurs when bright or radiant light interferes with a driver's vision. Common sources of glare include sunlight and the headlamp beams of oncoming vehicles, particularly during nighttime driving, when headlights impair a driver's ability to see clearly, increasing the risk of accidents. While much research has focused on the impact of glare from opposing headlights, the effect of sunlight glare on driving, particularly traffic congestion and delays, has received less attention [36].

Glare negatively affects driving performance in four ways: causing temporary visual impairment, discomfort, increased recovery time after exposure, and biological loss of vision. The first aspect, disability, occurs when light scatters inside the eye, making it difficult for drivers to perceive their surroundings and leading to slower vehicle speeds and traffic slowdowns. Subjective discomfort is influenced by factors such as the light source's intensity, the driving task's complexity, and ambient light. For instance, bright headlights from oncoming vehicles at night can cause eye strain and distractions, leading to lapses in concentration and delayed reactions [37, 38].

Antin et al. [39] developed the De Boer scale to quantify glare discomfort, which measures variables such as the angle and intensity of the light source. While this scale effectively assesses discomfort caused by headlights in oncoming traffic, it has limitations in predicting specific behavioural outcomes, such as speed or lane position changes. The variability in human responses to glare means that the scale cannot fully account for individual differences in perception and tolerance. Despite its usefulness, these personal differences restrict the scale's ability to predict how glare influences driving behaviour, limiting its broader application. Table 4 in the original study outlines the De Boer scale, a tool used to assess glare discomfort in drivers. The scale measures variables such as the angle of the light source and the intensity of the glare, providing a standardised method for evaluating how glare affects drivers' comfort and vision. It has been applied in various studies to quantify the discomfort caused by glare, particularly from oncoming headlights at night. However, while the scale offers valuable insights into the discomfort experienced by drivers, its ability to predict specific behavioural outcomes, such as speed reduction or lane position adjustments, is limited. This limitation arises from individual differences in perception and glare tolerance, which can vary based on age, visual health, and experience with driving in challenging conditions [39]. Despite this, the De Boer scale remains a useful tool for understanding the general impact of glare on driver comfort, though its real-world applicability for predicting driving behaviour may require further refinement.

Table 4. The De Bore scale for glare discomfort [40]

Rating	Qualifier
1	Unbearable
2	
3	Disturbing
4	
5	Just Acceptable
6	
7	Satisfactory
8	
9	Not Noticeable

Moreover, Direct sunlight and glare from bright headlamps can cause significant discomfort for drivers, often leading to temporary blindness and forcing them to reduce speed. Several studies have examined factors influencing a driver's visual performance, such as age, visual health, and headlamp glare intensity [41]. Kimlin et al. [42] found that older individuals, particularly those with cataracts, are more susceptible to the negative effects of glare. However, most studies have focused on specific glare causes under controlled conditions, which may not fully reflect real-world driving scenarios. The recovery period after glare exposure varies by age and is another crucial factor affecting visual performance. Research indicates that older drivers recover more slowly than younger adults [43].

In this context, glare from sunlight, especially during daytime driving, contributes significantly to traffic incidents, as observed by Choi and Singh [44]. Road geometry, such as alignments and lane numbers, is critical in glare-related accidents. While much research has focused on headlight glare from oncoming traffic at night, there remains a gap in understanding how sunlight affects driver behaviour during the day. Choi and Singh [44] also noted a direct correlation between glare intensity and the collision rate. Hammad et al. [45] identified road characteristics, traffic conditions, and weather as primary risk factors in glare-related accidents. Key roadway parameters, such as geometry, surface conditions, and lane width, influence these incidents, with high traffic volume linked to increased collision rates and reduced fatalities [46].

In addition to glare, adverse weather conditions, including fog, rain, and snow, significantly impact traffic operations and increase the likelihood of accidents. Malin et al. [47] argue that poor visibility and reduced road friction during such conditions elevate traffic accident rates, often disrupting traffic flow and lowering vehicle speeds. Fog, in particular, is responsible for numerous severe injuries and fatalities due to its substantial reduction in visibility, and similar effects occur during heavy rain or snowfall [48]. Therefore, understanding driver behaviour under these challenging conditions is essential, especially in conjunction with variations in road and environmental factors.

5. METHODOLOGIES USED IN SEASONAL STUDIES

5.1 Data collection techniques

Data collection is a critical component of studying seasonal variations in driving behaviour. Accurate and comprehensive data allows researchers to identify patterns and draw meaningful conclusions about the impact of different seasons on driving. One of the primary techniques used in data collection is traffic surveillance systems, which include cameras and sensors installed along roadways to monitor traffic flow and gather data on vehicle speeds, headways, and traffic volumes. These systems provide continuous, real-time data invaluable for understanding how driving behaviours change with the seasons [49].

Another standard data collection method involves surveys and questionnaires distributed to drivers. These tools gather qualitative data on driver perceptions, attitudes, and self-reported behaviours in different seasonal conditions. For instance, surveys might ask drivers about their experiences driving in snow or extremely hot weather, their stress levels, and any changes they make to their driving habits during these times. This qualitative data complements the quantitative data collected from traffic surveillance systems, providing a more comprehensive picture of seasonal driving behaviours [50].

In addition to surveys and surveillance systems, researchers often use onboard diagnostics (OBD) devices installed in vehicles to collect detailed data on vehicle performance and driver behaviour. OBD devices can track various metrics, including speed, acceleration, braking patterns, and fuel consumption. This data is particularly useful for identifying how vehicle performance issues, such as engine overheating or reduced battery efficiency, correlate with different seasonal conditions. Figure 4 presents a streamlined process for handling test data gathered from the OBD systems of a Renault Meganne III before and after repair. The workflow starts with collecting torque data from two vehicles in `.csv` format and feeding it into 'OBD_T5c.exe', which extracts key parameters such as engine RPM, coolant temperature, and trip statistics. This data is then processed through various stages, including aggregation scripts and specific programs like `Coolant.exe` and `TimeShift.exe`, which analyse the engine's cooling behaviour and adjust cycle timings. The thermostat work cycle data is split and refined, followed by the generation of histograms to understand the performance metrics better. Finally, the processed data is input into Gnu plot and spreadsheet software for further analysis, creating detailed charts, tables, and statistical summaries of the vehicle's performance under different conditions [51].

Field and Naturalistic Driving Studies (NDS) are important data collection techniques. Ehsani et al. [52] emphasise the importance of Naturalistic Driving Studies (NDS) as a crucial method in transportation research. NDS collects real-world driving data, providing insights into drivers' behaviour in everyday driving situations. This approach involves monitoring participants in their vehicles under natural conditions without external intervention. The data collected is often extensive, including information on driver behaviour, vehicle performance, and the surrounding environment (e.g., road conditions, weather). The advantage of NDS is that it offers a more accurate representation of driving behaviour compared to simulated studies or crash reports, which might not capture the nuances of real-time decisions and reactions.

NDS has been particularly valuable in identifying the factors leading to crashes, near-crashes, and other risky driving behaviours. By capturing various variables, such as distraction, speed, and following distance, NDS can help researchers develop more effective safety interventions and policies. However, the paper also notes challenges, such as the vast amount of data that must be processed and concerns regarding privacy and consent. Despite these challenges, NDS remains a vital tool in advancing road safety research and understanding the complexities of driver behaviour in real-world scenarios. Figure 5 illustrates the visualisation of data from an Australian Naturalistic Driving Study (ANDS) conducted by Ehsani et al. [52]. The figure showcases a combination of multiple data sources collected during a driving session. These include vehicle telemetry (speed, acceleration, and gyroscopic data), a real-time map of the driver's route, and synchronised video feeds capturing the driver's behaviour and the external road environment. The graph tracks speed and acceleration, while the map plots the trip's trajectory. The video footage, divided into four quadrants, also captures different perspectives: the driver's face, the road ahead, and other in-vehicle angles. This comprehensive visualisation allows researchers to analyse driving behaviour, vehicle dynamics, and environmental factors in context, contributing to a deeper understanding of driver decision-making and road safety in natural conditions.

5.2 Modelling approaches

Modelling approaches play a crucial role in understanding and predicting the effects of seasonal variations on driving behaviour. Traffic simulation models are one of the primary tools used for this purpose. These models simulate the movement of vehicles on a road network, taking into account various factors such as traffic volume, road conditions, and driver behaviour. By adjusting the parameters to reflect different seasonal conditions, researchers can predict how traffic flow and safety are likely to be affected in different seasons [53].

Headway modelling, whether measured as time or distance headway, refers to the separation between successive vehicles in a traffic lane. Time headway is the time interval between two vehicles passing the same point on the road, usually measured from a common feature like the front bumper [53]. In contrast, distance headway refers to the space between vehicles. This study specifically focuses on time headway, using it to develop an empirical car-following model based on headway and speed. The model aims to predict drivers' behaviour by analysing the relationship between headways and the associated speeds of vehicles, particularly those travelling with headways of 5 seconds or less, defined as impeded vehicles. The field data for headway and speed were collected and subjected to regression analysis, a statistical technique that explores the connection between dependent and independent variables. A simple linear regression model was chosen for this study because it effectively captures the relationship between headway and speed, aligning with previous research findings [54, 55].

The car-following models developed in this study were categorised based on vehicle size, focusing on the relationship between headway and speed. Four vehicle size categories were identified: small-size vehicles (≤ 6 m), medium-size vehicles (6-≤10 m), large-size vehicles (10-20 m), and truck-size vehicles (> 20 m). Each category was analysed within four car-following classes, such as small-size vehicles following small-size vehicles (small-small) or small-size vehicles following medium-size vehicles (small-medium). The study ensured a strong predictive relationship by developing the model with headway as the dependent variable and speed as the independent variable, achieving an R-squared value of 95%, with a 5% significance level (α = 0.05). While weather and driver response time were recognised as influential, they were excluded from the model due to measurement difficulties, making speed the sole predictor of headway. The resulting model offers a practical tool for understanding driver behaviour across different vehicle categories under varying traffic conditions.

Understanding how CRI evaluates a driver's perception of accident severity is crucial to developing the relationship between speed and the Chosen Risk Index (CRI). CRI is derived from the vehicle's speed, length (calculated from the wheelbase and weight), and the time gap (TG) between vehicles. The formula for calculating distance headway (H) is given in Eq. (7) [46]. This formula states that the distance headway is the product of the speed of the following vehicle (*v*) and the time headway (*t*), as shown:

$$H_{distance} = vt \tag{7}$$

As the speed of a vehicle increases, so does the potential severity of any ensuing accident, which is reflected in the CRI. Eq. (8) [46] calculates the CRI by multiplying the speed of the following vehicle (V) by its weight (W) and dividing the result by the time gap (TG), as follows:

$$CRI = \frac{v \times w}{TG} \tag{8}$$

In this formula, *CRI* is the Chosen Risk Index, *V* is the speed of the following vehicle, *W* is the vehicle's weight, and *TG* is the time gap in seconds. The *CRI* is highly relevant to accident analysis, as it highlights the influence of a vehicle's speed and weight on the perceived severity of a crash during car-following scenarios. Although advanced technologies like weight-in-motion sensors can measure a vehicle's weight, these technologies are costly and require installation beneath the road surface. Instead, the vehicle's wheelbase is used as a proxy for weight, assuming that vehicles of the same dimensions (width, height, and density) have similar weights [46].

The speed values for calculating CRI were derived from field data and represented the mid-points of speed class intervals. This allowed the development of a CRI-speed relationship during car-following, with data calculated for both winter and summer conditions. Furthermore, the study introduces the concept of relative CRI (CRIRelative), which evaluates the change in perceived accident severity between seasons. CRIRelative is calculated as the ratio of the CRI in winter to the CRI in summer, representing the relative risk over a given speed range during car-following.

Another important modelling approach is the speed-flow modelling. The speed-flow relationship quantifies how vehicle speeds relate to the flow rate on a highway section. This relationship is determined by correlating field-measured flow rates at various intervals with their corresponding speed values. Graphically plotting these values allows one to establish the maximum flow rate and associated speed.

This study considers four vehicle classes to analyse the data. However, these classes are converted to their equivalent Passenger Car Units (PCU) to standardise the analysis. This conversion translates the influence of different vehicle sizes—small, medium, large, and trucks—into the effect of passenger cars, thereby incorporating them into the overall flow rate. Consequently, the flow rate is expressed in Passenger Car Units per hour (pcu/h) rather than vehicles per hour (veh/h) [46].

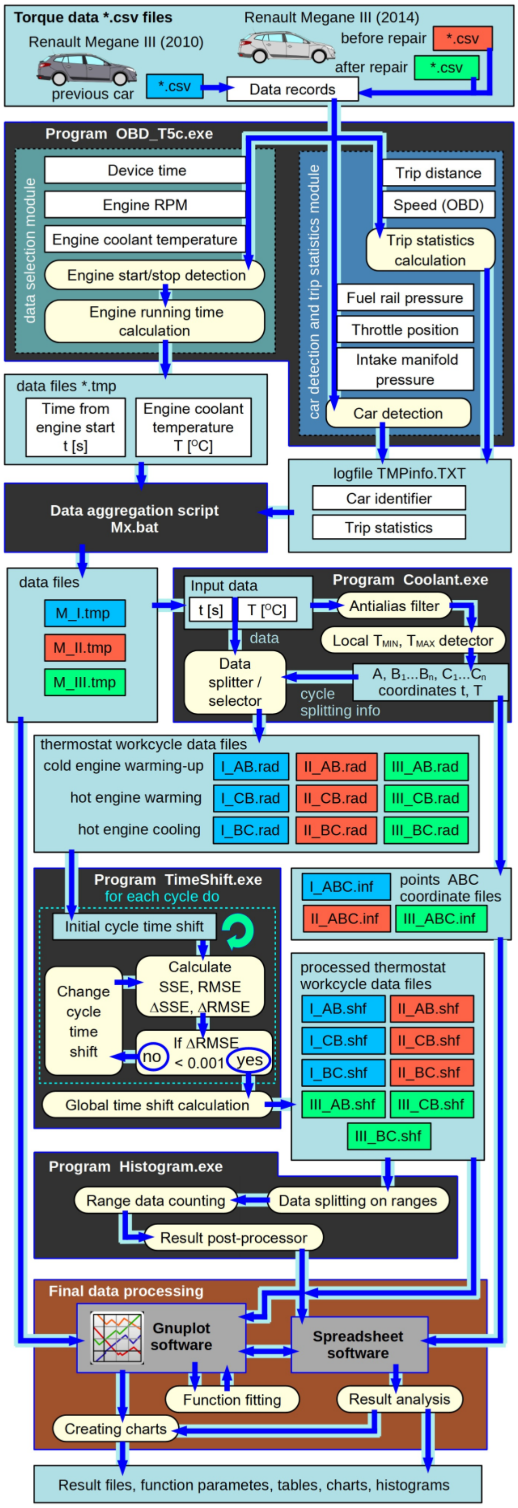

Figure 4. Scheme for processing test data read from OBD systems [51]

Figure 5. Visualisation of ANDS data [52]

The speed-flow relationship is derived from density plots of vehicles for each road under various weather conditions. Eq. (9) [46] represents this relationship:

$$Flow\ (v) = Density\ (D) \times Velocity\ (S) \tag{9}$$

Typically, the linear relationship between speed and density can be calculated using Eq. (10) [46]:

$$S = a\left(1 - \frac{D}{b}\right) \tag{10}$$

where, S = average speed (km/h), D = density (veh/km or veh/km/ln), a = free-flow speed (km/h), b = jam density (veh/km or veh/km/ln) [46].

Greenshields' model utilises this relationship to establish connections between flow-density and speed-flow. The flow-density relationship is articulated in Eq. (11) [46]:

$$S = a\left(1 - \frac{v/S}{b}\right) \tag{11}$$

where, v = flow rate. The flow rate and density can be calculated using Eq. (12) [46]:

$$v = bS - \left(\frac{b}{a}\right)S^2 \tag{12}$$

6. DISCUSSION

Studying car-following dynamics is critical to understanding how driver behaviours influence traffic flow and safety. A key concern in this field is the tendency for drivers to follow too closely, also known as "tailgating," which significantly increases the risk of accidents. Road user errors, such as misperception, distractions, and misjudgement of speed and distance, exacerbate this issue. Global data consistently show that human error is the leading cause of traffic incidents, as numerous studies across different countries have outlined. Tables 1 and 2 in the study underscore the widespread impact of driver mistakes, with misjudging speed and improper vehicle manoeuvres being common contributing factors.

Several models have been developed better to understand car-following behaviour, including empirical and mathematical approaches. These models examine how factors such as vehicle speed, distance headway, and driver reaction times influence safety and traffic flow. Empirical studies, like those conducted by Puan [11] and Connolly et al. [13], utilise real-world data to derive relationships between speed and following distance. Meanwhile, as Immers and Logghe [16] discussed, microscopic simulation models provide detailed insights into how vehicles interact within a traffic stream, capturing the dynamics of acceleration and deceleration in response to the lead vehicle. These models are instrumental in understanding driver behaviour under normal conditions, yet their applicability can be limited in more complex driving environments, such as intersections or two-lane roads, indicating the need for more context-specific models.

Environmental factors, particularly weather conditions, profoundly impact car-following behaviour. Adverse weather, including rain, fog, and snow, often compels drivers to reduce speed and increase headway to compensate for reduced visibility and traction. However, these adjustments are insufficient to mitigate the heightened risk of accidents, particularly rear-end collisions. Studies by Hamdar et al. [22] and Rakha et al. [17] show that adverse weather conditions reduce operating traffic speeds and impair visibility, which can increase the likelihood of accidents despite drivers' compensatory behaviours.

The interaction between environmental conditions and driver behaviour highlights the need for adaptive traffic management strategies. Real-time data collection and weather-controlled traffic systems have shown promise in mitigating the negative effects of adverse weather on road safety. For example, studies have demonstrated that implementing VMS and automated speed controls based on meteorological data can reduce mean traffic speeds and improve driving consistency under varying weather conditions. This type of proactive traffic management, as seen in studies by Rämä and Kulmala [29] and Goodwin [30], underscores the importance of integrating real-time weather information into traffic systems to enhance safety.

The effects of extreme weather and environmental conditions on driver behaviour are crucial to traffic management and road safety, particularly in regions experiencing significant seasonal variations. As previously discussed, the adverse conditions encountered during winter, such as snowfall and freezing temperatures, dramatically influence traffic patterns. These effects manifest through slower speeds, altered trip planning, and increased accident rates, as noted in regions like Canada. Similarly, sun glare, though a different environmental hazard, also disrupts driving behaviour by impairing visibility and reaction time, leading to increased congestion and accident risk.

Both phenomena—winter weather and sun glare—operate by impairing drivers' visual and operational capacity. Winter conditions typically reduce vehicle speeds and alter traffic volumes, particularly affecting passenger cars more than trucks. This is due to the flexibility of passenger car drivers in changing their schedules, whereas strict delivery timelines often bind trucks and require them to proceed regardless of adverse weather [35]. Additionally, as discussed, adverse winter conditions can shift traffic patterns, with vehicles migrating from poorly maintained roads to better-maintained highways. This shift creates unique traffic dynamics that further complicate winter driving conditions.

Conversely, the disruption caused by sun glare predominantly occurs during daylight hours, especially around sunrise and sunset. The bright light interferes with a driver's ability to see clearly, creating temporary visual impairments that result in slower driving speeds and increased congestion. Taghipour et al. [36] and Choi and Singh [44] highlight that sun glare contributes to a notable portion of traffic incidents, especially on roadways with specific geometries that amplify glare effects. This impact is compounded by other adverse weather factors, such as rain or fog, which further diminish visibility and affect traffic flow and safety outcomes.

The similarities between winter conditions and sun glare are their ability to disrupt the natural flow of traffic and challenge drivers' visual capacity. Both factors lead to adjustments in driver behaviour, whether through reduced speeds, increased headways, or altered trip routes. However, while winter conditions primarily create long-term disruptions influenced by road maintenance and snow removal efforts, sun glare tends to cause short-term visual impairments that resolve as the driver moves out of the direct line of light.

Incorporating these findings into a broader understanding of seasonal influences on driver behaviour highlights the need for adaptive traffic management strategies. Traffic systems must be flexible enough to respond to varying conditions, whether from prolonged winter storms, sudden sun glare, or shifting road conditions due to rain or fog. Research exploring how environmental factors, such as weather patterns, road geometries, and traffic volumes, interact with vehicle types offers crucial insights for policymakers and road safety professionals. These insights can enhance safety, reduce accident rates, and optimise traffic flow under challenging seasonal conditions. Given the dynamic nature of road safety, a more proactive approach is necessary, one that accounts for both short-term weather events and long-term infrastructure planning.

While significant progress has been made in understanding the effects of extreme weather on driver behaviour, several gaps remain. Although much research has focused on the impact of winter weather, sun glare, and fog on traffic patterns and accident rates, the specific behaviours of different vehicle types, particularly heavy trucks, are often overlooked. Due to their size and weight, trucks respond differently than passenger vehicles in adverse weather, which can influence overall traffic flow and safety. This study addresses this gap by examining the distinct driving behaviours of heavy vehicles during winter weather and sun glare, offering new insights into their impact on road safety.

Additionally, while individual environmental factors, such as glare or poor weather, have been studied, the combined effect of these hazards on driving performance remains underexplored. This research examines how multiple environmental conditions, such as sun glare and fog, influence driver behaviour, providing a more comprehensive understanding of how these factors increase accident risk. Furthermore, while much research has focused on the immediate effects of glare on vision, there is limited understanding of how drivers adjust their behaviour over extended exposure to such conditions. This study explores how drivers modify their habits over prolonged periods of adverse weather, offering a long-term perspective on how environmental hazards influence driving performance.

Another critical gap in the literature is the limited focus on real-world driving conditions. Most studies rely on controlled environments or simulations, which may not fully capture the complexities of actual driving situations, where factors such as road conditions, traffic volume, and the unpredictability of driver behaviour come into play. By examining real-world scenarios, this study provides more accurate and applicable insights into how seasonal variations affect driver behaviour in everyday traffic conditions. This approach enhances the findings' relevance and ensures that the results can inform practical traffic management strategies.

By addressing these gaps, this study provides a more nuanced understanding of how drivers respond to seasonal challenges and offers recommendations for improving road safety. The findings suggest the need for adaptive traffic management systems, such as dynamic signal controls, real-time weather alerts, and infrastructure modifications, tailored to the specific challenges of adverse weather. Additionally, the study emphasises the importance of considering the unique needs of different vehicle types, particularly heavy trucks, when designing safety measures. These insights contribute to academic knowledge and practical solutions that road safety professionals and policymakers can apply to enhance traffic flow and reduce accidents during adverse seasonal conditions.

The impact of regional differences in climate, infrastructure, and driving culture on driver behaviour and road safety is an important consideration that warrants further exploration. For example, regions with extreme winter conditions, such as Canada, experience significant disruptions to traffic patterns, with reduced vehicle speeds and increased accident rates due to snow, ice, and freezing temperatures. In contrast, regions with predominantly sunny climates, such as the Middle East, face challenges like sun glare, which impairs visibility and slows traffic, particularly around sunrise and sunset. Additionally, these regions' driving culture and infrastructure influence how drivers respond to environmental hazards. In areas with strict delivery timelines, such as certain urban regions, trucks may continue driving regardless of adverse weather, exacerbating risks.

On the other hand, in regions where road maintenance and weather-responsive traffic management systems are well-established, such as Scandinavian countries, drivers may experience fewer disruptions and risks. Understanding these regional variations is essential for tailoring traffic management strategies and road safety measures to specific environmental and cultural contexts, ensuring more effective interventions. Future research should explore these regional differences in greater detail to improve the applicability of findings across diverse geographical settings.

Potential areas for future research on the influence of weather and environmental conditions on driver behaviour are vast and essential for improving traffic safety and efficiency. One key area is the need for more detailed studies on the behaviour of different vehicle types, particularly heavy trucks, under extreme weather conditions. Understanding how weather impacts their behaviour is crucial for improving road safety and developing targeted traffic management strategies to reduce the likelihood of severe accidents. Research could focus on understanding how truck drivers adapt to adverse conditions, such as heavy snowfall or intense sun glare, and how this behaviour differs from passenger car drivers. Another promising area is investigating the combined effects of multiple environmental hazards, such as how rain, fog, and sun glare influence driving performance, congestion, and accident rates. Longitudinal studies could also explore how repeated exposure to these conditions affects drivers' long-term behaviour and adaptability. Also, future research could focus on real-world driving scenarios using advanced vehicle sensors, traffic simulations, and big data analytics to capture the complexity of driver behaviour in varying weather conditions and across diverse road environments. This research could also delve deeper into the role of technology, such as adaptive lighting systems, in mitigating the negative effects of glare and improving safety outcomes. By addressing these potential research areas, we can develop more targeted strategies to enhance traffic management and road safety in the face of seasonal weather challenges.

7. CONCLUSIONS

This comprehensive review highlights the significant impact of environmental conditions on road safety, particularly how extreme hot and cold weather affect driving performance, leading to increased accident rates and more aggressive driving behaviours. The synthesis of findings from various studies emphasises the importance of developing targeted interventions to address seasonal challenges. For example, improving road maintenance during winter and implementing public awareness campaigns about heat-related fatigue could help mitigate risks and enhance traffic safety.

However, several gaps in the literature remain. Future research should focus on integrative studies that explore the combined effects of multiple environmental factors and longitudinal studies to track changes in driver behaviour over time. Furthermore, demographic differences in responses to seasonal changes and psychological aspects like Seasonal Affective Disorder need more attention. These areas are crucial for creating more effective and comprehensive road safety strategies.

To advance the field, future studies should explore how regional differences in climate, infrastructure, and driving culture may influence the observed effects of environmental conditions on driving behaviour. This understanding could inform the development of region-specific road safety policies and interventions. Ultimately, policymakers and authorities can enhance road safety year-round by adopting a more holistic and longitudinal approach and incorporating mental health considerations into road safety programs. Continuous adaptation of traffic management strategies to seasonal variations will ensure safer driving conditions across diverse environments and seasons.

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