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Research paper

Assessing AI-based eco-driving solutions for reducing GHG emissions in green transportation systems

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ABSTRACT

The transportation sector in the Kingdom of Saudi Arabia (KSA) is a major contributor to greenhouse gas (GHG) emissions, driven by the country's heavy reliance on oil and fossil fuels. Transitioning to a green and sustainable transport system is critical for reducing emissions and aligning with Saudi Arabia's Vision 2030 goals of diversifying its economy and promoting environmental sustainability. Thus, this research examined the adoption of a green sustainable transport system to reduce GHG emissions and reduce dependence on fossil fuels for sustainable development in the KSA. The study evaluates various factors and Artificial Intelligence (AI)-based eco-driving solutions to systematically implement green transportation systems. In this study, the Fuzzy Analytical Hierarchy Process (FAHP) method is applied to evaluate the five factors and eighteen sub-factors crucial for developing a green transportation system in the country. Next, the Fuzzy Technique for Order of Preference by Similarity to Ideal Solution (FTOPSIS) method is used to prioritize the most significant AI-based eco-driving solutions for the implementation of smart and green transportation in KSA. The findings of the FAHP show that environmental impact (33 %) is the most crucial factor, followed by regulatory compliance (21.3 %) and economic viability (16.9 %). The FTOPSIS indicates that the smart navigation system ($CC_i = 0.682$) is the most critical AI-based eco-driving solution because this can help reduce GHG emissions and increase the efficiency of traffic regulation in the country. The electric and hybrid vehicle integration ($CC_i = 0.585$) and carbon footprint tracking systems ($CC_i = 0.355$) are the next most significant solutions. This study is helpful in reducing GHG emissions, supporting sustainable development, and guiding policymakers toward effective green transport initiatives.

Abbreviations

KSA	Kingdom of Saudi Arabia
FAHP	Fuzzy Analytical Hierarchy Process
FTOPSIS	Fuzzy Technique for Order of Preference by Similarity to Ideal Solution
AI	Artificial Intelligence
GHG	Greenhouse Gas
CO_2	Carbon Dioxide
SDGs	Sustainable Development Goals
MGI	Middle East Green Initiative
SGI	Saudi Green Initiative
MCDM	Multi-Criteria Decision Making
TFN	Triangular Fuzzy Numbers
CCi	Closeness Coefficient

1. Introduction

Environmental concerns have become a global issue, urging nations to act swiftly to combat global warming and support sustainable development (Khurshid et al., 2024). Global warming has presented several challenges because of climate change, including environmental deterioration, rising levels of greenhouse gas (GHG) emissions, shifting weather patterns, and melting glaciers (Mariappan et al., 2022). In this regard, the transportation sector is a significant source of GHG emissions, as its dependence on nonrenewable fuels and environmentally harmful substances has led to a substantial global increase in emissions (Nasir et al., 2024). In the Kingdom of Saudi Arabia (KSA), the transportation industry has a major impact on environmental issues. The

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most dominant means of transport in the nation is conventional private vehicles, which substantially increase GHG emissions and negatively impact the environment. Pollution affecting the atmosphere and traffic jams resulting from the use of these vehicles might lead to enhanced energy usage (Sharmilaa & Ilango, 2022; Zhang & Batterman, 2013). Data science and technological advancements, such as intelligent transportation systems and Artificial Intelligence (AI), play a key role in addressing these challenges. These technologies have the potential to significantly reduce GHG emissions from conventional vehicles. Intelligent transportation systems are revolutionizing modern transportation, reshaping the movement of people and goods (Elassy et al., 2024). Therefore, the transportation industry plays a vital role in creating job opportunities, driving economic growth, and improving overall well-being (Khurshid, Khan, & Cifuentes-Faura, 2023). In this regard, the transition toward green and sustainable transportation supports the Sustainable Development Goals (SDGs) and the Paris Agreement. In particular, the study aligns with SDG 9 (Industry, Innovation and Infrastructure), SDG 11 (Sustainable cities and communities), and SDG 13 (Climate Action) through resilient and low-carbon transportation solutions and identifying the sector's role in reducing GHG emissions.

The Saudi Arabian NEOM, AlUla, and Red Sea projects are the most striking, as they combine cutting-edge technology to reduce GHG emissions and promote sustainable development. However, Saudi Arabia's transportation sector contributes significantly to its emissions. Carbon dioxide (CO_2) emissions in the KSA's transportation sector have risen from four metric tons in 1972 to 132 metric tons in 2021, with an average annual growth rate of 8.26 %. Moreover, it is forecast that CO_2 emissions will increase to 184 million tons by 2030 (Alam et al., 2022; Shannak et al., 2022). In addition, approximately 25 % of the GHG emissions are attributable to the transportation industry. Currently, fossil fuels still provide 95 % of the energy used for transportation worldwide (United Nations, 2021). A strong increase in GHG emissions was observed in developing nations, with Asia producing the most emissions overall in 2019. Transportation accounts for 28 % of total energy consumption and 57 % of the world's oil demand. Saudi Arabia has established the Middle East Green Initiative (MGI) to reduce climate change and fulfill global climate targets (Saudi Vision 2030, 2022; 2022). The MGI may increase regional collaboration and build infrastructure to cut emissions, protect the environment, boost climate change efforts, and create economic opportunities for the region. The KSA would host an MGI summit and contribute 2.5 billion US$ to assist MGI projects and governance in expediting MGI goals (Middle East Green Initiative, 2022; Vision 2030 serves as the foundation for modern Saudi Arabia's development. This vision is characterized by a dynamic economy, an environmentally conscious approach, and a thriving society aimed at achieving sustainable development. As part of this initiative, Saudi Arabia has announced several flagship projects, including NEOM, AlUla, and The Red Sea Project. These endeavors highlight the country's dedication to sustainability, innovation, and international collaboration.

Road transport consumes significant quantities of fossil fuels and accounts for a significant proportion of global CO_2 and pollutant emissions. Thus, numerous countries are phasing out fossil fuel vehicles, including gasoline, diesel, kerosene, and fuel oil. The KSA has also taken the lead in reducing the environmental impact of conventional fuel-based transportation by establishing an eco-friendly Saudi Green Initiative (SGI) program and supporting global efforts to develop the hydrogen sector. Therefore, decarbonizing the transportation sector is likely necessary for the KSA to reach net-zero GHG emissions by 2060. Moreover, Saudi Vision 2030, 2022 seeks to digitalize the logistics sector via blockchain, robotics, AI, and automation. Data science and technology, like AI and intelligent transportation systems, are addressing these issues. This can lower traditional car energy use and GHG emissions for sustainable development (Magazzino et al., 2025). Advancements in technologies have led to the development of a sustainable road transport system (Liu et al., 2025). In this regard, eco-driving is the best strategy for a sustainable future in the world. Eco-driving refers to sustainable driving practices that aim to reduce the environmental impacts of vehicles (Huang et al., 2018). The objective was to reduce fuel consumption, decrease CO_2 emissions, and increase energy efficiency. To cope with the effects of climate change, hybrid and electric vehicles have emerged as promising solutions for minimizing CO_2 emissions while transforming transportation habits (Kumar et al., 2024; Singh, 2023). Eco-driving is a low-cost and fast solution to achieve a decrease in fuel consumption and CO_2 emissions.

This study identifies and ranks key criteria and AI-based eco-driving solutions for implementing a green transportation system in the KSA. To achieve this objective, the study used the Fuzzy Analytical Hierarchy Process (FAHP) and the Fuzzy Technique for Order of Preference by Similarity to Ideal Solution (FTOPSIS) methods for comprehensive analysis. First, the FAHP method was utilized to assess various factors and sub-factors that evaluate the feasibility of implementing AI-based eco-driving practices for a country's green transportation system. Second, the FTOPSIS method ranks different AI-based eco-driving solutions to help the country adopt green transportation systems. This approach is very useful in handling uncertainty and imprecision because it enables more realistic results in this decision-making problem. Thus, this research can help the government, stakeholders, and decision-makers determine the most suitable AI-based eco-driving solutions for adopting green transportation in the KSA. The research is directive in defining current and future transportation scenarios and assisting decision-makers in making significant decisions. This research is significant because it employs a comprehensive decision-making approach to address the critical issue of GHG emissions in the transportation sector of KSA, in line with Saudi Vision 2030, 2022 and net-zero emissions goals. Therefore, the FAHP and FTOPSIS methods distinguish this study by handling imprecision and uncertainty, providing realistic findings in this multifaceted scenario. Aside from that, the emphasis on green transportation systems based on AI technologies to reduce GHG emissions is relevant in the context of global efforts to combat climate change and advance sustainable development. The study offers useful information to policymakers and industry players on the most effective approaches to sustainable transportation.

The remainder of this paper is organized as follows. Section 2 provides the theoretical background for this study. Section 3 presents the identified factors and eco-driving solutions. Section 4 outlines the methodology used in the research, while the results are presented in Section 5. Section 6 gives a discussion and its implications. Finally, Section 7 summarizes the conclusions and several policy recommendations.

2. Theoretical background

Transportation stands out as one of the most important sectors contributing to global GHG emissions (Fan et al., 2023). This impact can be seen most profoundly in areas such as Saudi Arabia, where new urban centers and economic development have necessitated the use of cars and, hence, breeding emissions. To overcome this problem, new concepts need to be explored and employed, for instance, AI-linked solutions for eco-driving are considered to improve the eco-efficiency of transport networks (Abduljabbar et al., 2019; Tselentis et al., 2023). Traditional eco-driving utilizes driver training, fuel-efficient driving techniques, and static route optimization, and provides moderate fuel and emission reductions. Its performance depends fully on maintaining proper driving behaviors. AI-powered eco-driving systems utilize real-time data alongside predictive models and automated features to enhance travel efficiency while minimizing fuel consumption and pollution. This technology continuously evolves by learning and adjusting to various factors, including road conditions, vehicle performance, and environmental influences, ultimately providing more effective and comprehensive solutions. The integration of AI-based solutions creates a critical path to sustainable transportation systems.

The transport sector is responsible for approximately 15 % of the global GHG emissions (EPA, 2024). Despite utilizing advanced technologies, the country is still required to meet the United Nations targets in terms of SDGs and the Paris Agreement. Developing countries need to establish new and sustainable transport infrastructure systems, but their resources are limited. These countries require new approaches that can help them bypass conventional patterns and rapidly learn from each other. According to data on the CO_2 emissions of countries in 2020, Saudi Arabia emitted approximately 712.59 million tons of CO_2 equivalent. This makes Saudi Arabia the world's eleventh-largest CO_2 emitter from combustible fuels; thus, its total share contribution is 1.6 % of global emissions (IEA, 2024). Given that the transport sector contributes a significant portion of Saudi Arabia's total emissions, it is necessary to manage these emissions. Nevertheless, in 2018, the transport sector accounted for 21 % of total CO_2 emissions in Saudi Arabia. This underlines the importance of transport in the country's overall GHG emissions. The burning of fossil fuel within automobiles (particularly for transport) and the higher rate of increase in economic growth and urbanization have further promoted the use of vehicles, which has boosted GHG emissions.

Moreover, eco-driving also entails strategies that drivers can adopt in their vehicles in order to use less fuel and thus emit less (Fafoutellis et al., 2021). These are smooth acceleration and deceleration, speed stability, and traffic flow anticipation (Li et al., 2019). Li et al. (2016) demonstrated that eco-driving has significant potential to reduce emissions in China's road transport sector, and this approach could also be beneficial in Saudi Arabia. Their research showed that eco-driving, along with other measures, can reduce CO_2 and pollutant emissions, thereby improving air quality and mitigating pollution. Therefore, integrating AI into eco-driving solutions presents a valuable approach to making transportation more sustainable. AI can enhance driver behavior by providing real-time feedback based on data utilization. As highlighted by Alanazi and Alenezi (2023), the adoption of electric vehicles and the integration of smart technologies to improve sustainable transportation can significantly reduce emissions. Their study emphasizes the importance of a well-designed framework and an integrated intelligent system to address issues like traffic congestion and emissions.

In this study, the flow of the analysis can be described by the following steps using the co-occurrence keywords analysis. Fig. 1 presents the co-occurrence keywords, particularly used in the transportation studies.

The economic implications of adopting AI-based eco-driving solutions are multifaceted. With a focus on the optimization of fuel consumption, these solutions can yield significant direct and indirect cost reductions for car owners and companies. Also, less fuel expenditure further improves the efficiency of sustainable transportation activities and makes them financially profitable. The environmental benefits are also accruable because low emissions are healthy for the environment and align with SDGs (Ali et al., 2021). However, there are some issues that negatively influence the application of AI-based eco-driving solutions. This model possesses various challenges, among which are high infrastructure costs, technological integration challenges, and the awareness and knowledge of the public. However, the challenges can only be overcome through collective action with government

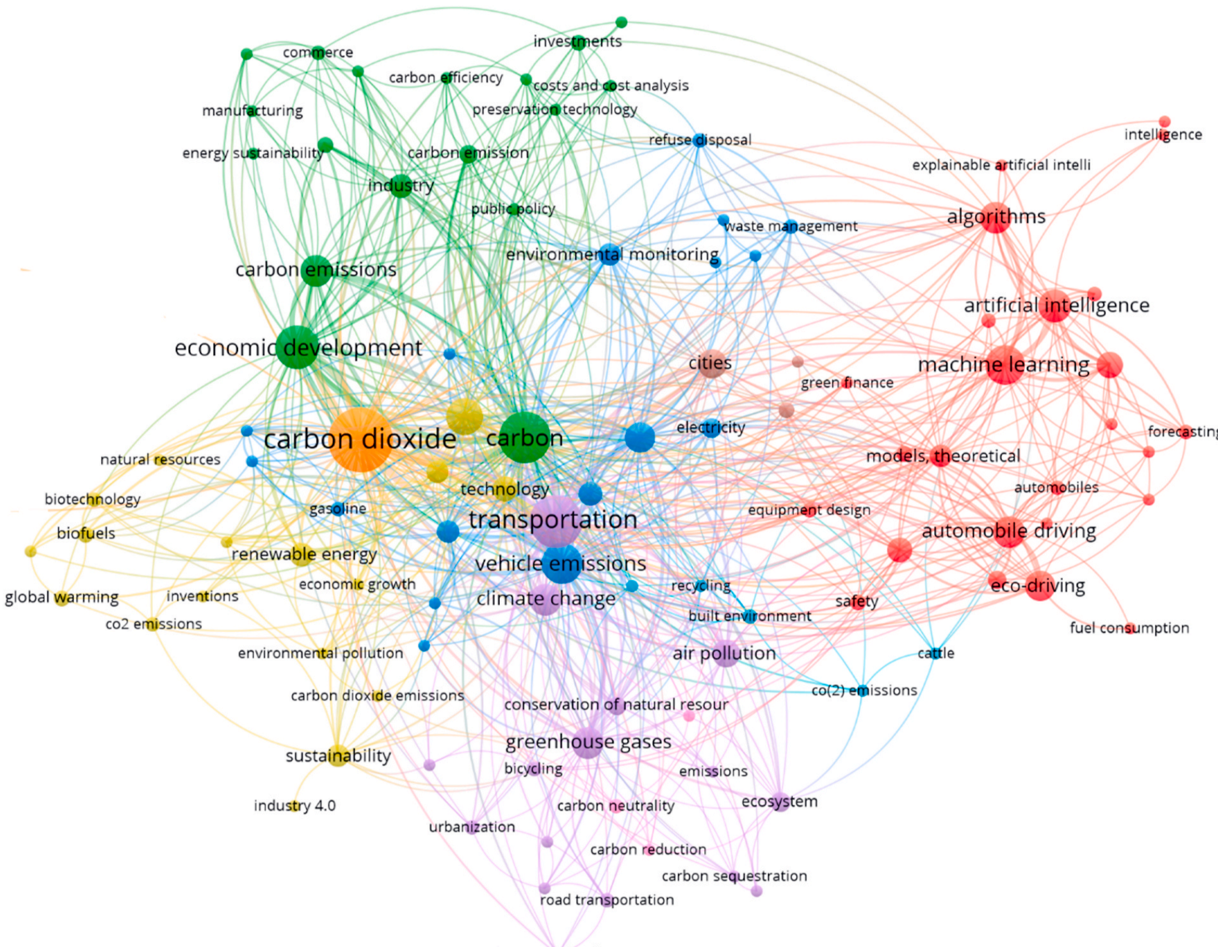

Fig. 1. Co-occurrence keywords in transportation studies.

involvement in partnership with industry players and tech players. For example, actions in the sphere of public-private partnerships can mean the creation of the infrastructure needed and the encouragement of adequate ecological behaviors (Maslova, 2020). Khurshid, Khan, Saleem, Cifuentes-Faura, and Cantemir Calin (2023) highlighted the crucial role of transportation sector innovation in mitigating emissions and reducing welfare costs. Advanced econometric analyses confirmed that green transport technologies and renewable energy integration significantly curb environmental degradation, supporting carbon neutrality and sustainable transport targets. Li et al. (2023) presented the role of carbon taxes and mitigation technologies in reducing emissions across OECD regions. Findings suggested that sector-specific innovations – particularly in water treatment, energy transmission, and transportation – significantly curb emissions, supporting the SDGs target for climate action and sustainable growth. According to related studies, the adoption of AI-based eco-driving applications holds strong prospects for contributing to sustainability improvements in the KSA transport sector.

In the context of transportation and sustainability, MCDM methods play a crucial role in addressing the complex and often conflicting objectives that need to be balanced to achieve sustainable transport solutions. These methods enable decision-makers to assess and prioritize various transportation alternatives based on multiple factors, including environmental impact, economic feasibility, social equity, and technological readiness. MCDM methods have been widely applied in transportation sustainability studies. For example, sustainable transport decision (Moslem et al., 2019), public transportation (Nassereddine & Eskandari, 2017), road transport sustainability (Wang et al., 2022), efficiency of transportation companies (Stević et al., 2022), and transport safety (Guo et al., 2024). Although there is increasing interest in implementing environmentally friendly transportation systems, research focusing specifically on Saudi Arabia remains limited. A significant research gap exists regarding the key factors and sub-factors that influence the adoption of these systems within the country, particularly in relation to its unique regulatory, economic, and cultural context. Furthermore, a research gap is evident in using fuzzy-based AHP and TOPSIS to systematically rank these factors and solutions. This is the very first analysis of the KSA context, which is missing from the literature. This gap suggests that there is still room for more focused work, with an emphasis on exploring the adoption of green transportation practices in the country. FAHP and FTOPSIS approaches are significant for overcoming any complex decision-making problem. As such, it remains pertinent to fill this gap in the pursuit of deriving practical and strategic solutions for the achievement of the Saudi Vision 2030, 2022.

3. Methods

The factors and AI-based eco-driving solutions have been obtained after data collection through a comprehensive literature review. Therefore, five factors, eighteen sub-factors, and five solutions were identified to adopt a green transportation system in KSA, aligning it with Saudi Vision 2030, 2022 for sustainable development. In the next phase, the decision-making approaches are used for the analysis. First, the FAHP is used to evaluate the factors and sub-factors. Next, the FTOPSIS method is used to prioritize AI-based eco-driving solutions in order to mitigate GHG emissions for green transportation systems in the KSA. These decision-making methods are very significant in addressing any multi-faceted problem. Fig. 2 illustrates the decision-making framework of the research.

3.1. Case study analysis

The transportation sector poses a massive challenge for the KSA, as

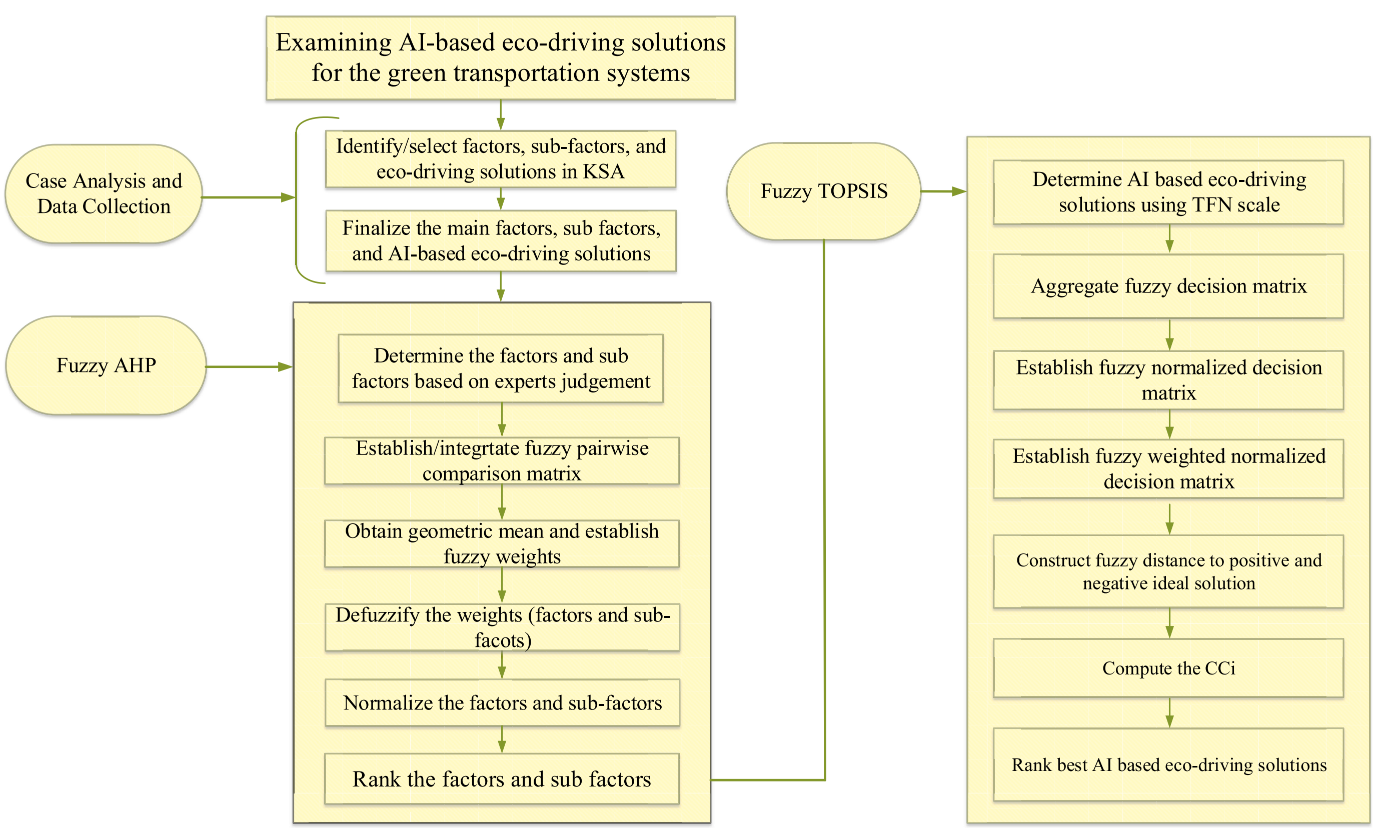

Fig. 2. The decision-making model.

Table 1
The key factors and sub-factors.

Main factor	Sub-factor	Brief description	Reference
Economic viability (C1)	Infrastructure cost (C11)	Assesses the financial implications of developing and maintaining the infrastructure required for the deployment of eco-driving solutions.	Fafoutellis et al. (2021)
	Cost-effectiveness (C12)	Analyze the environmental benefits of eco-driving while assessing the cost-effectiveness of the proposed solutions to ensure that the developed strategies are economically viable.	Li et al. (2024)
	Economic impact on local businesses (C13)	Assesses the positive impact of eco-driving solutions on local businesses, such as transportation services, for the economic development plan.	(Adamczak et al., 2020; Xu et al., 2022)
Environmental impact (C2)	Energy efficiency (C21)	Specializes in evaluating the performance of energy efficiency in transportation systems with special reference to energy effectiveness and improvement on available energy resources.	(Laimon et al., 2022; Lajunen, 2014)
	Carbon emissions reduction (C22)	Evaluates the efficiency of the eco-driving solutions in reducing CO_2 emissions from the cars that are on the road for environmental stewardship.	Allison and Stanton (2019)
	Air quality improvement (C23)	Evaluate the extent to which the strategies positively impact air quality by reducing pollutants and ensuring a healthier and cleaner environment.	Glazener and Khreis (2019)
User experience and education (C3)	Educational programs' effectiveness (C31)	Measures the success of educational programs in raising awareness and understanding among users about eco-driving practices and their environmental impact.	(Jeffreys et al., 2018; Tu et al., 2022)
	User-friendly interfaces (C32)	Evaluates the design and usability of interfaces within the eco-driving solutions, ensuring that users can easily navigate and interact with the systems.	Gimpel et al. (2022)
	User feedback mechanisms (C33)	Examines the presence of feedback mechanisms that allow users to provide input and suggestions, fostering a collaborative approach to system improvement.	(Chada et al., 2023; Xu et al., 2021)
	Awareness and understanding of eco-driving practices (C34)	Assesses the overall awareness and comprehension of users regarding the eco-driving practices promoted by the implemented strategies.	Fafoutellis et al. (2021)
Collaboration and partnerships (C4)	Contributions to global sustainable initiatives (C41)	Assesses the role of eco-driving solutions in contributing to global sustainability initiatives. This would position KSA as a leader in sustainable urban development.	Tu et al. (2022)
	Collaborations with technology providers (C42)	Examines partnerships with technology providers to ensure access to cutting-edge strategies and expertise.	Chen et al. (2022)
	Engagements with local businesses (C43)	Measures the extent of collaboration with local businesses in implementing and supporting eco-driving solutions for local economic development.	Goes et al. (2020)
	Public-private partnerships (C44)	Evaluates collaborations between public and private entities to enhance the effectiveness and sustainability of eco-driving solutions.	Chen et al. (2022)
Regulatory compliance (C5)	Alignment with environmental standards (C51)	Examines the extent to which the strategies align with established environmental standards. This would contribute to KSA's commitment to sustainable development.	Xu et al. (2021)
	Adherence to local and international regulations (C52)	Ensures that the eco-driving solutions comply with both local and international regulations, addressing legal requirements and standards.	Goes et al. (2020)
	Collaboration with regulatory bodies (C53)	Assesses the level of collaboration and communication with regulatory bodies to facilitate a transparent and compliant approach to eco-driving solutions.	Chen et al. (2022)
	Legal and ethical considerations (C54)	Addresses legal and ethical aspects associated with the implementation of AI-based eco-driving solutions, ensuring responsible and ethical practices.	(Kumar, 2024; Ryan, 2020)

conventional fossil fuel vehicles emit high levels of GHGs and are a threat to the environment. It is a fact that the country is undergoing tremendous growth in terms of urbanization as well as the development of the economy, which is likely to enhance demand for transport. The use of internal combustion engines in automobiles has contributed significantly to GHG emissions, as well as increasing air pollution and traffic jams in the country. The presented environmental effects have dangerous consequences for public health and the sustainable development of the country. The solution needs faster implementation because KSA aims to meet international climate targets while achieving Vision 2030 objectives that involve building a more sustainable economy and reducing GHG emissions. The eco-driving solutions provide a potential way for fuel reduction, emission reduction and energy effectiveness in the transportation system. Therefore, AI-based eco-driving solutions can be regarded as a realistic strategy. Automation through world-class technological advancements, such as intelligent transportation systems, can help KSA meet its fuel requirements within the shortest time possible while simultaneously reducing air pollution and road traffic density. This transition towards smart and sustainable transportation is not only required to counteract the negative effects on the environment, but it also holds massive potential for improving the well-being of the Saudi Arabian population as well as addressing the country's developmental goals.

3.2. Data collection

In this study, various factors and sub-factors have been identified through a literature review for implementing a green transportation system in KSA. These factors are very critical in determining AI-based eco-driving solutions for sustainable and resilient transportation systems in the country. Later, professional experts from the fields of academia, engineering, research institutes, and policymakers were consulted to provide important feedback on the development of a green transportation system in KSA to reduce GHG emissions for sustainable economic, environmental, and social development. The questionnaire survey was distributed to eleven experts via e-mail; this questionnaire consisted of five factors, eighteen sub-factors, and five AI-based eco-driving solutions. The feedback from eleven experts was validated for further analysis. A questionnaire survey was given to each expert, with a scale of importance provided for their opinions on factors, sub-factors, and eco-driving solution strategies. The demographic information of the experts and the questionnaire survey is given in the Supplementary Material.

3.3. Proposed factors and sub-factors for the green transportation system

This study identified various key factors and sub-factors after a comprehensive literature review/data collection process, which are useful for adopting green transportation systems in the KSA. These factors are effective in mitigating these challenges and are relevant for incorporating AI-based eco-driving solutions. Table 1 provides a brief overview of the proposed factors and sub-factors.

3.4. Proposed AI-based eco-driving solutions

AI-based eco-driving solutions for the green transportation system in

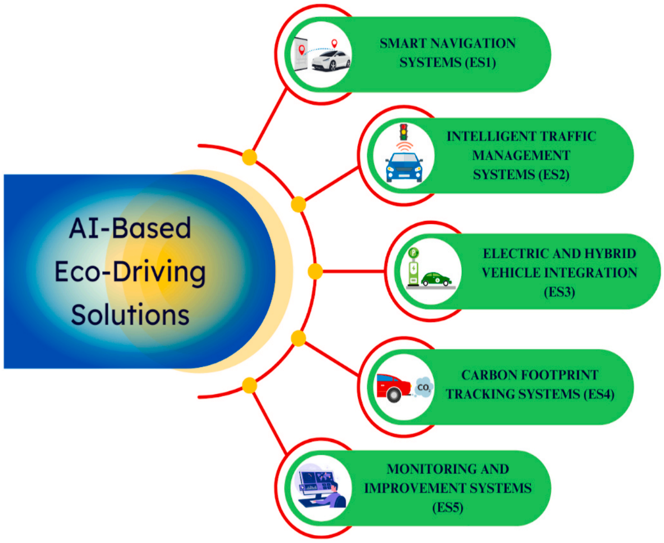

Fig. 3. The list of AI-based eco-driving solutions.

the KSA represent an innovative approach to sustainable development. These solutions aim to revolutionize the dynamics of transportation, aligning with KSA's commitment to achieving SDGs. This study determines AI-based eco-driving solutions based on the identified criteria. Fig. 3 shows the five key eco-driving solutions assessed in the analysis. Table 2 provides a brief overview of each solution.

3.5. FAHP method

The AHP method is a valuable tool for problem-solving in any decision-making activity (Karam et al., 2021). This approach solves complex decision-making problems by placing them in a hierarchical manner to comprehend the challenges that are easy to solve in a better way. It assists with the handling of qualitative data so that they can be converted or dealt with as quantitative data (Jain et al., 2018). In the present study, we employed the FAHP technique for its capacity to deal with fuzziness and imprecision in the experts' judgment during the decision-making process, thus making it appropriate to tackle the involved uncertainties and complexities when evaluating multiple criteria. Fuzzy set theory is more than capable of dealing with multi-faceted problems in decision-making (Zadeh, 1978).

Nevertheless, the adoption of FAHP is not without limitations. One of the primary concerns is its dependency on expert judgment, which can introduce subjectivity and potential bias. While fuzzy logic helps reduce the rigidity of exact numerical inputs, the process still relies on human experts whose evaluations can be influenced by personal experience, cognitive limitations, or contextual misunderstanding. To mitigate this, the study consulted multiple domain experts and applied consistency ratio checks to ensure the reliability of pairwise comparisons. Another limitation of FAHP lies in its complexity in criteria comparison, especially when dealing with a large number of criteria and sub-criteria. The need to perform fuzzy pairwise comparisons across multiple levels of hierarchy can be computationally intensive and time-consuming. Moreover, the aggregation of fuzzy judgments and defuzzification procedures requires careful handling to avoid information loss or distortion. Despite these limitations, FAHP was deemed more appropriate for this study compared to other methods such as Entropy, Criteria Importance Through Intercriteria Correlation (CRITIC), or Best Worst Method (BWM). Objective methods like Entropy or CRITIC derive weights based solely on data variability and correlation, which do not reflect expert knowledge or contextual relevance, which is critical in sustainability

Table 2
Proposed AI-based eco-driving solutions for green transportation systems.

Eco-driving solution	Brief explanation	Reference
Smart navigation systems (ES1)	AI-driven navigation systems go beyond conventional route planning. Enriched with machine learning capabilities, these systems factor in real-time data on traffic, road conditions, and weather, providing drivers with intelligent suggestions for minimizing their environmental impact.	(Bhatti et al., 2021; Khalil et al., 2024)
Intelligent traffic management systems (ES2)	AI algorithms optimize traffic flow dynamically, minimizing congestion and reducing fuel consumption. Predictive modeling anticipates peak traffic hours, enabling efficient rerouting and contributing to a significant reduction in carbon emissions.	(Abduljabbar et al., 2019; Dikshit et al., 2023; Hamidi & Kamankesh, 2018)
Electric and hybrid vehicle integration (ES3)	AI analyzes usage patterns and demand to optimize the placement of charging stations, ensuring convenient access for the public. Promotes the use of electric and hybrid vehicles, reducing carbon emissions and aligning with KSA's vision.	(Liu et al., 2019; Pritima et al., 2022)
Carbon footprint tracking systems (ES4)	AI is instrumental in tracking and analyzing the carbon footprint of transport-related activities. Integration into transportation systems provides personalized insights and recommendations for minimizing carbon emissions.	(Bibri et al., 2024; Fernández, 2019)
Monitoring and improvement systems (ES5)	AI-based systems change with circumstances. Continuous monitoring and improvement involve a feedback loop that incorporates user insights, environmental data, and technological advancements.	(Alahi et al., 2023; Javaid et al., 2022)

and policy-driven decisions. BWM, while more efficient in reducing pairwise comparisons, lacks the fuzziness component needed to manage ambiguity in stakeholder inputs. Therefore, FAHP offered a balanced compromise between structured pairwise logic and the flexibility of fuzzy theory, making it well-suited for the complex, expert-driven evaluation of AI-based eco-driving solutions. This study employs triangular fuzzy numbers (TFN) to arrive at the weights of the criteria and sub-criteria. The linguistic variable scales are presented in Table 3 on the basis of the TFN.

The following key steps of the FAHP method are applied (Singh et al., 2023).

Step 1. The judgment matrix can be defined as:

$$\widetilde{D^k} = \begin{bmatrix} \widetilde{a_{11}^k}\ \widetilde{a_{12}^k} \cdots \widetilde{a_{1n}^k} \\ \widetilde{a_{21}^k}\ \widetilde{a_{22}^k} \cdots \widetilde{a_{2n}^k} \\ \cdots\cdots\cdots\cdots \\ \widetilde{a_{n1}^k}\ \widetilde{a_{n2}^k} \cdots \widetilde{a_{nm}^k} \end{bmatrix} \tag{1}$$

Step 2. The geometric mean for multiple decision-maker's preferences is used:

$$\widetilde{r}_{ij} = \left(\prod_{k=1}^{K} \widetilde{r}_{ij}^{K}\right)^{1/K} \tag{2}$$

Step 3. Aggregate the data of all decision-makers. Thus, the following is the pairwise comparison matrix:

$$\widetilde{R} = \begin{bmatrix} \widetilde{r}_{11} & \cdots & \widetilde{r}_{1n} \\ \vdots & \ddots & \vdots \\ \widetilde{r}_{n1} & \cdots & \widetilde{r}_{nm} \end{bmatrix} \tag{3}$$

Step 4. The geometric mean of fuzzy values for each criterion is calculated as (Buckley, 1985):

$$\widetilde{R} = \left(\prod_{j=1}^{K} \widetilde{r}_{ij}\right)^{\frac{1}{n}} \tag{4}$$

Step 5. Compute the fuzzy weights:

$$\widetilde{w}_i = \widetilde{r}_i^{\otimes} \left(\widetilde{r}_1^{\oplus} \widetilde{r}_2^{\oplus} \ldots^{\oplus} \widetilde{r}_n\right)^{-1} = (lw_i, mw_i, uw_i) \tag{5}$$

Step 6. The center of area approach, proposed by Chou and Chang (2008), is used to de-fuzzified $\widetilde{w}_i$ since they are still TFN:

$$M_i = \frac{lw_i, mw_i, uw_i}{3} \tag{6}$$

Step 7. Normalize M_i:

$$N_i = \frac{M_i}{\sum_{i=1}^{n} M_i} \tag{7}$$

Later, the FTOPSIS method is employed to prioritize the AI-based eco-driving solutions.

3.6. FTOPSIS method

The TOPSIS method is widely recognized as a key MCDM approach, extensively utilized by researchers, policymakers, stakeholders, and academicians across various fields. This approach is helpful in calculating the distance between a positive ideal solution, which is the closest distance, and a negative ideal solution, which is the farthest distance in any problem related to decision-making (Alyamani et al., 2024). However, it has certain limitations in real-world applications, as it often fails to offer clear insights into the problem and leaves some issues vague and undefined. Therefore, the FTOPSIS method is computationally simple and suitable for processing multiple alternatives, and can be adapted to fuzzy environments. This method is well-suited for the handling of uncertainty and imprecision that are usually present in the MCDM process. FTOPSIS was selected due to its ability to integrate expert uncertainty through fuzzy set theory while maintaining a structured distance-based approach for evaluating alternatives against positive ideal and negative ideal solutions, making it particularly suitable for complex, sustainability-oriented decisions such as the assessment of AI-based eco-driving strategies. Fig. 4 shows the TFN scale adopted to rank AI-based eco-driving solutions (Han & Trimi, 2018).

Table 3
The TFN scale.

Importance	Linguistic variable	TFN	Inverse
1	Equally important	(1,1,1)	(1,1,1)
3	Slightly important	(2,3,4)	(4,3,2)
5	Important	(4,5,6)	(6,4,5)
7	Strongly important	(6,7,8)	(8,7,6)
9	Extremely important	(9,9,9)	(9,9,9)
2,4,6,8	Intermediate value		

The key steps of the FTOPSIS method are the following (Singh et al., 2023).

Step 1. Construct the fuzzy decision matrix:

$$l_{ij} = min(l_{ijk}) \tag{8}$$

$$m_{ij} = \frac{1}{k}\sum_{k=1}^{K} m_{ij}^{k} \tag{9}$$

$$u_{ij} = max(u_{ijk}) \tag{10}$$

Step 2. Normalize the fuzzy decision matrix:

$$\widetilde{R} = [\widetilde{r}_{ij}] \tag{11}$$

where i = 1,2, …,m and j = 1,2, …,n.

$$\widetilde{r}_{ij} = \left(\frac{l_{ij}}{u_j^+}, \frac{m_{ij}}{u_j^+}, \frac{u_{ij}}{u_j^+}\right) \text{(benefit criteria)} \tag{12}$$

$$\widetilde{r}_{ij} = \left(\frac{l_j^-}{u_{ij}}, \frac{l_j^-}{m_{ij}}, \frac{l_j^-}{l_{ij}}\right) \text{(cost criteria)} \tag{13}$$

Step 3. Construct the weighted normalized fuzzy decision matrix:

$$\widetilde{V} = [\widetilde{v}_{ij}] \tag{14}$$

where

$$\widetilde{v}_{ij} = \widetilde{r}_{ij} \times w_j \tag{15}$$

Step 4. Compute the distance between fuzzy positive ideal solution (A_i^+) and fuzzy negative ideal solution (A_i^-):

$$A^+ = \left(\widetilde{v}_1^+, \widetilde{v}_2^+, \widetilde{v}_3^+, \ldots, \widetilde{v}_n^*\right) \tag{16}$$

$$A^- = \left(\widetilde{v}_1^-, \widetilde{v}_2^-, \widetilde{v}_3^-, \ldots, \widetilde{v}_n^-\right) \tag{17}$$

Step 5. Compute the Closeness Coefficient (CC_i):

$$CC_i = \frac{A_i^-}{A_i^+ + A_i^-} \tag{18}$$

A_i^+ is the distance from fuzzy positive ideal solution and A_i^- is the distance from fuzzy negative ideal solution.

4. Analysis of the results

Based on a hierarchical structure, the FAHP and FTOPSIS methods are applied. First, the FAHP method was used to evaluate the factors and sub-factors. Subsequently, the FTOPSIS method was utilized to rank the most relevant solutions. The detailed analysis obtained from these approaches for factors/sub-factors, and eco-driving solutions is given in Supplementary section. Fig. 5 presents the hierarchically structured problem of this study.

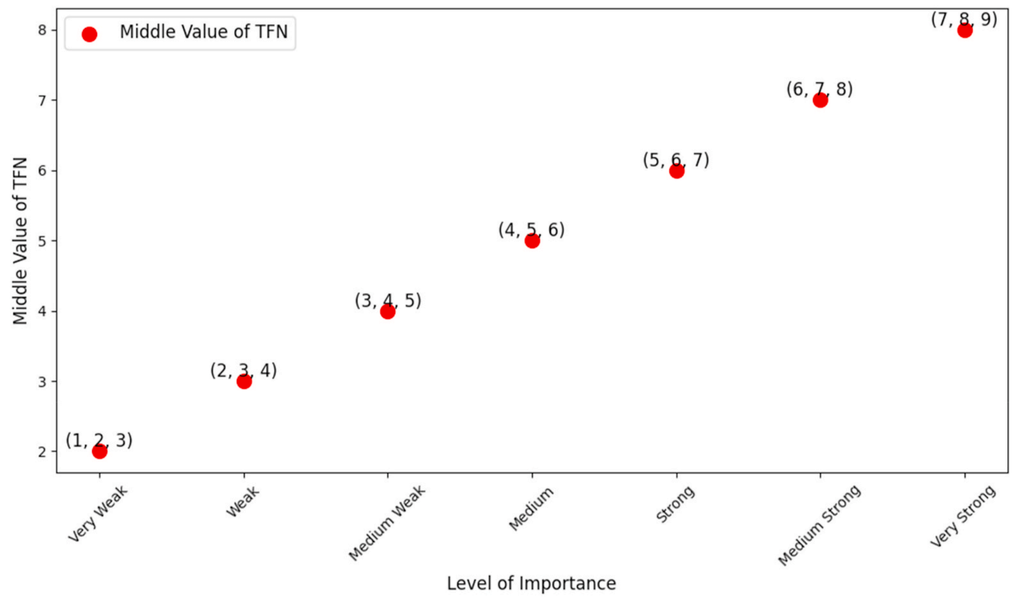

Fig. 4. TFN scale for analyzing eco-driving solutions.

4.1. Results of main factors using FAHP

The five main factors were assessed and ranked with respect to solving the multifaceted decision-making goal of the study. Table 4 presents the prioritized orders of the main factors. The results show that environmental impact is the most critical factor (C2, w = 0.330). This high importance indicates a strong emphasis on sustainability and ecological responsibility in the national transportation sector. This aligns with global efforts to combat climate change and highlights a country's dedication to reducing its carbon footprint. The environmental impact signifies that any AI-based eco-driving solution must effectively contribute to minimizing GHG emissions and improving overall environmental health (Olawade et al., 2024). The focus on environmental impacts suggests that policies and projects prioritize technologies and practices that offer substantial ecological benefits. The second key factor is regulatory compliance (C5, w = 0.213). This shows how important it is to comply with both local and global environmental standards and regulations. Also, meeting international adherence can help in building partnerships worldwide and attract international investments because compliance with global standards is perceived as a signal of reliability and commitment to best practices. Next, economic viability is listed as the third most important factor in showing the importance of the cost-effectiveness and financial sustainability of eco-driving solutions (C1, w = 0.169). Projects and technologies that provide significant environmental benefits at a reasonable cost are likely to receive priority funding. Economic viability can help attract private investments and make public investments more effective. Investor stakeholders will only participate in activities that yield some measure of returns besides adding to the economic base. The fourth main factor is represented by collaboration and partnerships (C4, w = 0.151). With this realization, there is a need to ensure that constructive relationships are nurtured with the various stakeholders. Communicating with local businesses and partnering with technology suppliers are two major aspects of the effective implementation of AI-based eco-driving practices. Lastly, the level of user experience and education (C3, w = 0.137) is considered the least influential in the choice of green transportation system in KSA.

4.2. Results of sub-factors of economic viability (C1)

Table 5 presents the prioritizing order of the sub-factors of economic viability (C1). The results show that the economic impact on local businesses (C13) is the most important sub-factor (50.00 %) for adopting eco-driving solutions, leading to significant economic growth at the community level. Local businesses can benefit from investment opportunities in various fields, such as vehicle maintenance, charging station management, and AI support services. The economic impact on local business operations should be prioritized for achieving widespread communal support to establish eco-driving measures. Infrastructure cost (C11) is discovered as a second relevant sub-factor (27.10 %) for considering the financial implications of developing and maintaining the infrastructure required for eco-driving solutions. Careful budgeting and the efficient use of resources are essential for managing infrastructure costs effectively. Furthermore, cost-effectiveness (C12) is identified as the third sub-factor (22.90 %). This indicates that projects and solutions need to demonstrate a good return on investment (ROI) by achieving significant environmental benefits without incurring excessive costs. Therefore, cost-effective measures can strengthen stakeholder confidence, attract funding opportunities, and encourage widespread adoption. Prioritization of these economic factors ultimately guarantees that eco-driving solutions remain financially sustainable without mutilating the environment.

4.3. Results of sub-factors of environmental impact (C2)

Table 6 displays the ranks of sub-factors for environmental impact (C2). The findings show that air quality improvement is ranked as the highest priority sub-factor (39.80 %). This sub-factor is crucial for reducing pollutants and enhancing air quality in Saudi Arabia. This focus reflects the direct impact of air quality on public health and environmental well-being. Cleaner air can enhance residents' quality of life and reduce the economic burden of health issues related to pollution. To achieve substantial improvements in air quality, policies are likely to prioritize measures that reduce GHG emissions from the transportation sector. Carbon emissions reduction is determined to be the next important sub-factor (34 %), indicating a strong commitment to addressing climate change by lowering GHG emissions. This sub-factor

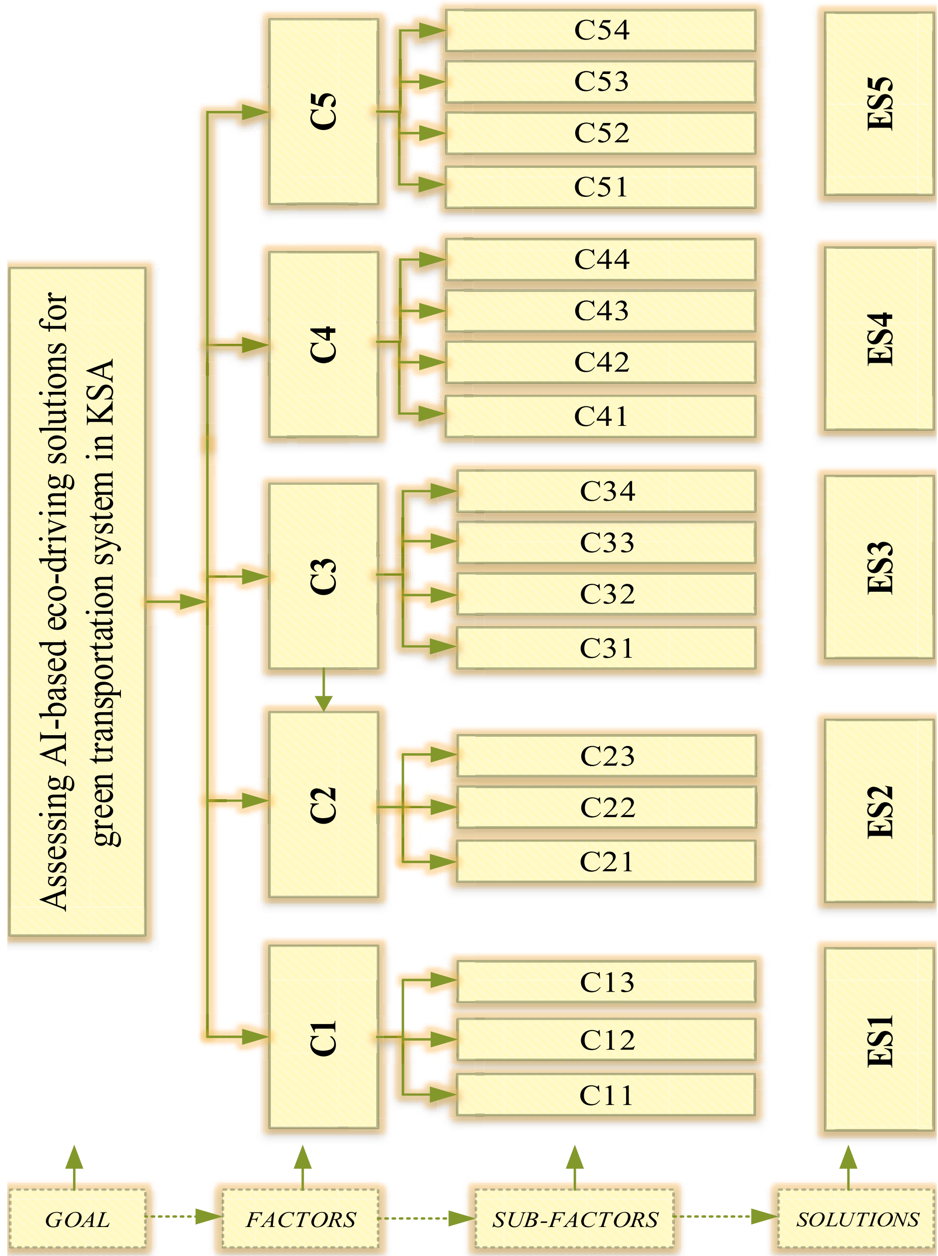

Fig. 5. The hierarchically structured model.

Table 4
The outcome of main factors.

Main factor	Fuzzy Geometric Mean	Fuzzy Weights	Defuzzified Weights	Normalized Weight	Percentage	Rank
Economic viability (C1)	0.778,0.885,1.02	0.129,0.168,0.221	0.173	0.169	16.9 %	3rd
Environmental impact (C2)	1.519,1.743,1.99	0.252,0.33,0.432	0.338	0.330	33 %	1st
User experience and education (C3)	0.636,0.721,0.83	0.105,0.137,0.18	0.141	0.137	13.7 %	5th
Collaboration and partnerships (C4)	0.68,0.794,0.93	0.113,0.15,0.202	0.155	0.151	15.1 %	4th
Regulatory compliance (C5)	0.993,1.133,1.26	0.165,0.215,0.275	0.218	0.213	21.3 %	2nd

Table 5
The outcome of sub-factors with respect to economic viability (C1).

Sub-factor	Fuzzy Geometric Mean	Fuzzy Weights	Defuzzified Weights	Normalized Weight	Percentage	Rank
Infrastructure cost (C11)	0.792,0.861,0.942	0.225,0.270,0.327	0.274	0.271	27.1 %	2nd
Cost-effectiveness (C12)	0.652,0.728,0.815	0.186,0.229,0.283	0.232	0.229	22.9 %	3rd
Economic impact on local businesses (C13)	1.436,1.596,1.755	0.409,0.501,0.609	0.506	0.500	50 %	1st

aligns with Saudi Vision 2030, 2022 regarding international climate commitment and national sustainability goals. Consequently, effective strategies in the transportation sector, such as promoting electric vehicles and optimizing traffic flow through AI-based systems, can significantly reduce the GHG emissions for sustainable development. The focus on reducing carbon emissions supports the long-term sustainability of the transportation sector. This ensures that transportation practices align with global efforts to limit temperature rise and reduce environmental degradation. Finally, energy efficiency is prioritized as a third-ranked sub-factor (26.20 %). Energy-efficient practices can lead to significant cost savings for both individuals and the government.

4.4. Results of sub-factors of user experience and education (C3)

Table 7 depicts the ranking of sub-factors for user experience and education (C3). The results show that awareness and understanding of eco-driving practices are the most critical sub-factors within user experience and education (35.30 %). This emphasizes the need for widespread awareness campaigns and educational initiatives. Increasing awareness and understanding of eco-driving practices can lead to significant behavioral changes among drivers. Educated drivers are more likely to adopt eco-friendly driving habits that can reduce fuel consumption and emissions. User-friendly interfaces are recognized as the second key sub-factor. User-friendly interfaces have the potential to significantly increase the adoption rates of eco-driving technologies and systems. When drivers find the technology simple to use, they are more likely to integrate it into their daily routine. Thus, this sub-factor can assist and ensure that interfaces are user-friendly, making eco-driving solutions accessible to a broader range of users. Next, the effectiveness of educational programs was identified as the third priority sub-factor. Developing effective educational programs requires collaboration between various stakeholders, including government bodies, educational institutions, and transportation organizations. The effectiveness of educational programs can be measured through assessments and feedback. Finally, user feedback mechanisms are shown as the last-ranked sub-factor. User feedback is essential for the continuous improvement of eco-driving technologies and practices.

4.5. Results of sub-factors of collaboration and partnerships (C4)

Table 8 displays the ranking order of sub-factors with regard to collaboration and partnerships (C4). The findings highlight that public-private partnership is the most important sub-factor (28.20 %). The private sector often brings innovation and cutting-edge technology, which are crucial for developing advanced eco-driving solutions and intelligent transportation systems. Government involvement can provide necessary regulatory and policy support to facilitate the adoption of green technologies and practices. Contributions to global sustainability are found to be the second sub-factor (25.50 %). This initiative can enhance KSA's reputation and effectiveness in addressing global environmental challenges. Aligning with global initiatives ensures that local transportation projects meet international standards and best practices, enhancing their credibility and effectiveness. Likewise, collaborations with technology providers are recognized as the third important sub-factor (23.50 %). This shows the importance of integrating advanced technologies into sustainable transport solutions. Therefore, collaborations with technology providers ensure access to the latest advancements in AI, IoT, and other technologies critical for sustainable transportation. Besides, technological innovation aids in formulating effective strategies to address environmental concerns (Khan & Khurshid, 2022). Finally, engagements with local businesses are presented as the least sub-factor (22.80 %). However, it remains a critical aspect of building a sustainable transportation system. Engagements with local businesses support economic development by creating opportunities for local enterprises to participate in and benefit from sustainable transport projects.

4.6. Results of sub-factors of regulatory compliance (C5)

Table 9 displays the classification of sub-factors for regulatory compliance (C5). The results indicate that adherence to local and international regulations is the most significant sub-factor (35.70 %) since it ensures that eco-driving solutions and practices comply with both local and international regulations for legal operations and integration into the broader transportation system. Compliance with regulations helps standardize practices across different regions and sectors, facilitating the smoother implementation and enforcement of green transportation initiatives. Alignment with environmental standards is acknowledged as the second critical sub-factor (23.30 %). Alignment with environmental standards ensures that eco-driving practices effectively reduce environmental impacts such as carbon emissions and energy consumption (Mehmood et al., 2024). Next, collaboration with regulatory bodies is shown to be a third-ranked sub-factor (22.30 %) in facilitating effective regulatory oversight and support for green and sustainable eco-driving practices. Lastly, legal and ethical considerations are identified as the fourth sub-factor (18.70 %).

4.7. Results of overall sub-factors

The final weights of sub-factors have been identified by multiplying the weights of the main factors by their particular sub-factors. Fig. 6 lists the final weights of the sub-factors. This indicates that air quality

Table 6
The outcome of sub-factors with respect to environmental impact (C2).

Sub-factor	Fuzzy Geometric Mean	Fuzzy Weights	Defuzzified Weights	Normalized Weight	Percentage	Rank
Energy efficiency (C21)	0.729,0.793,0.879	0.216,0.260,0.320	0.266	0.262	26.2 %	3rd
Carbon emissions reduction (C22)	0.936,1.04,1.142	0.278,0.341,0.416	0.345	0.340	34 %	2nd
Air quality improvement (C23)	1.081,1.213,1.35	0.321,0.398,0.492	0.404	0.398	39.8 %	1st

Table 7
The outcome of sub-factors with respect to user experience and education (C3).

Sub-factor	Fuzzy Geometric Mean	Fuzzy Weights	Defuzzified Weights	Normalized Weight	Percentage	Rank
Educational programs' effectiveness (C31)	0.839,0.945,1.056	0.176,0.225,0.287	0.23	0.225	22.5 %	3rd
User-friendly interfaces (C32)	0.992,1.133,1.285	0.208,0.27,0.35	0.276	0.27	27 %	2nd
User feedback mechanisms (C33)	0.551,0.629,0.739	0.116,0.15,0.201	0.156	0.152	15.2 %	4th
Awareness and understanding of eco-driving practices (C34)	1.294,1.485,1.683	0.272,0.354,0.458	0.361	0.353	35.3 %	1st

Table 8
The outcome of sub-factors with respect to collaboration and partnerships (C4).

Sub-factor	Fuzzy Geometric Mean	Fuzzy Weights	Defuzzified Weights	Normalized Weight	Percentage	Rank
Contributions to global sustainable initiatives (C41)	0.897,1.017,1.167	0.197,0.253,0.33	0.26	0.255	25.5 %	2nd
Collaborations with technology providers (C42)	0.843,0.955,1.057	0.185,0.238,0.299	0.241	0.235	23.5 %	3rd
Engagements with local businesses (C43)	0.797,0.907,1.051	0.175,0.226,0.298	0.233	0.228	22.8 %	4th
Public-private partnerships (C44)	0.994,1.136,1.288	0.218,0.283,0.365	0.289	0.282	28.2 %	1st

improvement (C23) is the highest-ranked factor for enhancing the environment for sustainable development (w = 0.1313). This reflects the primary goal of eco-driving solutions, which is to improve air quality by reducing the pollutants emitted by vehicles. In the context of KSA's transportation system, focusing on air quality is essential for public health and aligns with the nation's broader environmental sustainability goals. Reducing carbon emissions (C22) is the second most important sub-factor (w = 0.1123) with respect to the decision-making goal of this study. Moreover, energy efficiency (C21) is considered the third impactful sub-factor (w = 0.0864). While enhancing energy efficiency is a valuable goal, its immediate effects on the environment and user experience may not be as significant as those of other sub-factors. Nonetheless, energy-efficient driving practices and technologies are essential components of sustainable transportation systems. The positive economic impact on local businesses (C13) is a significant factor (w = 0.0842) in evaluating the economic viability of eco-driving solutions. This indicates that the potential benefits to local businesses, such as the increased demand for eco-friendly transportation services and related technologies, are highly valued. Compliance with local and international regulations (C52) is the fifth critical sub-factor (w = 0.0760) for the legal implementation of eco-driving solutions.

4.8. Results of AI-based eco-driving solutions using FTOPSIS

Table 10 shows the classifications of AI-based eco-driving solutions. Fig. 7 presents the final ranking of solutions based on the highest values of *CCi*. The results clarify that AI-driven smart navigation systems are the most effective solutions in the context of green transportation in the KSA. These systems utilize real-time data on traffic conditions, road conditions, and weather to optimize vehicle routing. The capability of these systems to dynamically adjust routes in response to changing conditions ensures that environmental impacts are minimized, making them a top priority for sustainable transportation solutions. The integration of electric and hybrid vehicles is determined to be a second critical solution because it is highly valued owing to its direct impact on reducing carbon emissions and promoting renewable energy sources. AI plays a critical role in optimizing the placement of charging stations and analyzing usage patterns to support the adoption of these vehicles. This solution aligns with KSA's broader environmental goals and Vision 2030, which emphasizes the transition to cleaner energy and sustainable practices. Carbon footprint tracking systems are the third most important AI-based solutions. This solution measures and analyzes the emissions of transportation and activities. AI-driven systems that provide personalized insights and recommendations help users and organizations make informed decisions to reduce their carbon footprints (Olawade et al., 2024).

4.9. Sensitivity analysis for robustness analysis

The sensitivity analysis was conducted to validate the robustness and reliability of the decision-making process for the five AI-based eco-driving solutions (ES1–ES5). Using the One-At-A-Time (OAT) approach, a structured form of what-if analysis (Annad & Lefkir, 2022; Więckowski & Sałabun, 2023), we examined how ±5 % changes in the weights of the main criteria (C1–C5) affected the CC_i scores and resulting rankings. The adjusted weights are presented in Table 11, while Table 12 shows the changes in prioritizing order of eco-driving solutions. The base case, reflecting the original weight distribution, yielded the following ranking order: ES1 > ES3 > ES4 > ES5 > ES2, with Smart navigation systems (ES1) emerging as the top choice due to its balanced performance across economic viability (C1), environmental impact (C2), and regulatory compliance (C5). The primary finding is the robustness of ES1, which maintained its position as the top-ranked alternative across most scenarios. For instance, adjusting C1 (±5 %) had a minimal impact on the rankings, reinforcing ES1's stability. However, certain criteria exhibited more pronounced effects: reducing C2 (Environmental Impact) by −5 % shifted focus to Electric & hybrid vehicle integration (ES3), highlighting the critical role of environmental considerations in reordering priorities. Conversely, increasing C2 strengthened ES1's dominance, emphasizing the importance of balancing environmental sustainability. Regulatory compliance (C5) also played a significant role: increasing its weight slightly boosted ES3's position, while decreasing it reinforced ES1's

Table 9
The outcome of sub-factors with respect to regulatory compliance (C5).

Sub-factor	Fuzzy Geometric Mean	Fuzzy Weights	Defuzzified Weights	Normalized Weight	Percentage	Rank
Alignment with environmental standards (C51)	0.854,0.959,1.078	0.182,0.233,0.299	0.238	0.232	23.2 %	2nd
Adherence to local and international regulations (C52)	1.268,1.481,1.687	0.27,0.359,0.468	0.366	0.357	35.7 %	1st
Collaboration with regulatory bodies (C53)	0.794,0.911,1.069	0.169,0.221,0.297	0.229	0.223	22.3 %	3rd
Legal and ethical considerations (C54)	0.688,0.773,0.87	0.146,0.187,0.241	0.192	0.187	18.7 %	4th

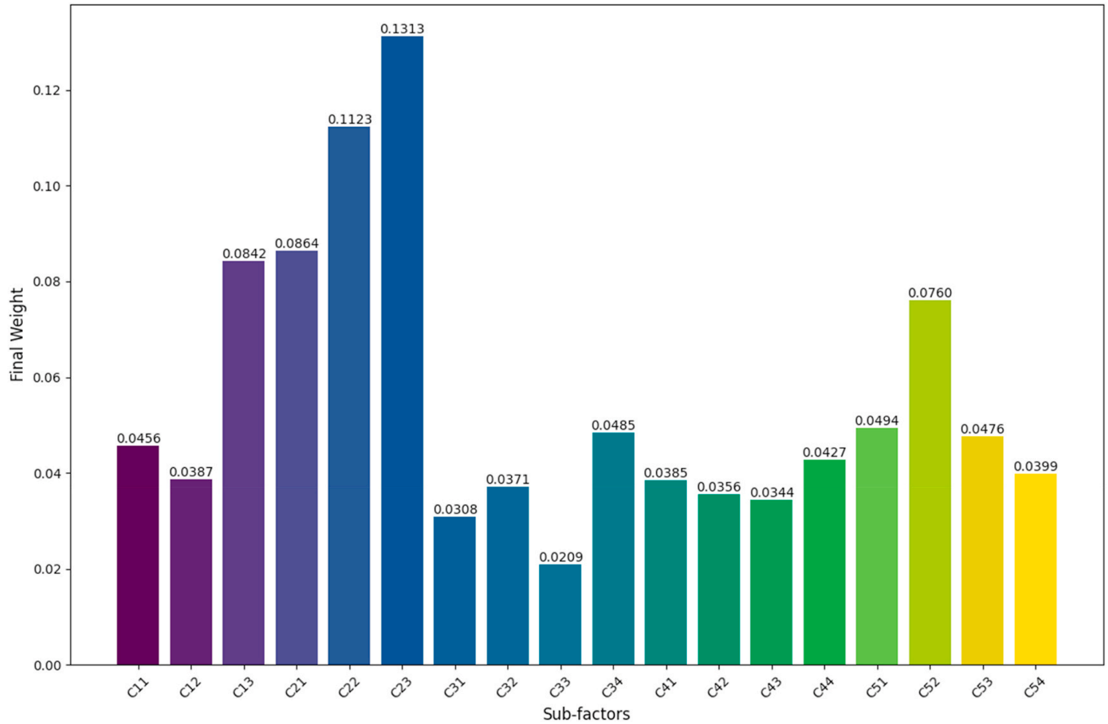

Fig. 6. Final weights of overall sub-factors.

Table 10
The outcome of AI based eco-driving solutions.

AI-based eco-driving solution	A_i^+	A_i^-	CC_i	Rank
Smart navigation systems (ES1)	0.096	0.205	0.682	1
Intelligent traffic management systems (ES2)	0.210	0.082	0.282	5
Electric and hybrid vehicle integration (ES3)	0.126	0.178	0.585	2
Carbon footprint tracking systems (ES4)	0.202	0.111	0.355	3
Monitoring and improvement systems (ES5)	0.188	0.102	0.352	4

lead. Additionally, Carbon footprint tracking systems (ES4) and Monitoring & improvement systems (ES5) demonstrated stable performances, consistently ranking 3rd and 4th, respectively, while Intelligent traffic management systems (ES2) remained at the bottom. Overall, the sensitivity analysis confirms the robustness of ES1 as the preferred solution under most scenarios.

5. Discussion, theoretical, and practical implications

The decision-making approaches play an increasingly essential role

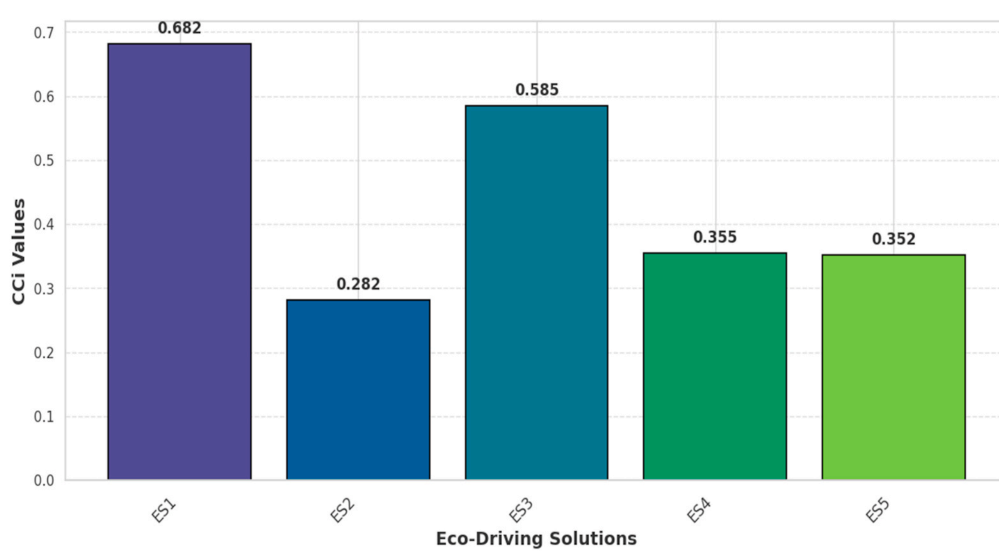

Fig. 7. Final ranking of solutions based on the highest value of CC_i.

Table 11
Adjusted weights with different scenarios.

Case No.	Scenario (factor)	C1	C2	C3	C4	C5
Case 1 (base case)	Original Weights	0.169	0.33	0.137	0.151	0.213
Case 2	Increase C1 (+5 %)	0.178	0.323	0.133	0.147	0.22
Case 3	Decrease C1 (−5 %)	0.16	0.337	0.142	0.156	0.205
Case 4	Increase C2 (+5 %)	0.163	0.347	0.133	0.147	0.21
Case 5	Decrease C2 (−5 %)	0.174	0.314	0.142	0.156	0.215
Case 6	Increase C3 (+5 %)	0.166	0.327	0.144	0.147	0.217
Case 7	Decrease C3 (−5 %)	0.172	0.333	0.13	0.154	0.212
Case 8	Increase C4 (+5 %)	0.166	0.327	0.133	0.159	0.216
Case 9	Decrease C4 (−5 %)	0.172	0.333	0.142	0.144	0.21
Case 10	Increase C5 (+5 %)	0.166	0.327	0.133	0.147	0.227
Case 11	Decrease C5 (−5 %)	0.172	0.333	0.142	0.154	0.2

Table 12
Changes in ranking of eco-driving solutions.

Case No	Scenario (factors)	Eco-driving solution	CC_i score	Rank
Case 1 (base case)	Original Weights	ES1	0.682	1
		ES3	0.585	2
		ES4	0.355	3
		ES5	0.352	4
		ES2	0.282	5
Case 2	Increase C1 (+5 %)	ES1	0.679	1
		ES3	0.587	2
		ES4	0.356	3
		ES5	0.353	4
		ES2	0.283	5
Case 3	Decrease C1 (−5 %)	ES1	0.684	1
		ES3	0.584	2
		ES4	0.355	3
		ES5	0.352	4
		ES2	0.282	5
Case 4	Increase C2 (+5 %)	ES1	0.69	1
		ES3	0.578	2
		ES4	0.348	3
		ES5	0.346	4
		ES2	0.275	5
Case 5	Decrease C2 (−5 %)	ES3	0.6	1
		ES1	0.675	2
		ES4	0.358	3
		ES5	0.355	4
		ES2	0.285	5
Case 6	Increase C3 (+5 %)	ES1	0.685	1
		ES3	0.583	2
		ES4	0.354	3
		ES5	0.351	4
		ES2	0.281	5
Case 7	Decrease C3 (−5 %)	ES1	0.68	1
		ES3	0.586	2
		ES4	0.356	3
		ES5	0.353	4
		ES2	0.283	5
Case 8	Increase C4 (+5 %)	ES1	0.683	1
		ES3	0.585	2
		ES4	0.355	3
		ES5	0.352	4
		ES2	0.282	5
Case 9	Decrease C4 (−5 %)	ES1	0.681	1
		ES3	0.586	2
		ES4	0.356	3
		ES5	0.353	4
		ES2	0.283	5
Case 10	Increase C5 (+5 %)	ES3	0.605	1
		ES1	0.678	2
		ES4	0.357	3
		ES5	0.354	4
		ES2	0.284	5
Case 11	Decrease C5 (−5 %)	ES1	0.685	1
		ES3	0.584	2
		ES4	0.355	3
		ES5	0.352	4
		ES2	0.282	5

in solving the problems associated with the achievement of sustainable transport. MCDM methods have been widely used in the transportation sector in the areas of various sustainability-related problems. These methods have been applied to assess and optimize public transportation schemes (Nassereddine & Eskandari, 2017). These decision-making techniques have also been useful in addressing problems of fuel efficiency, emission reductions, and congestion management with respect to road transport systems (Wang et al., 2022). Additionally, these methods have been used to make an efficient assessment of the performance of the transportation companies and safety (Guo et al., 2024; Stević et al., 2022). MCDM methods emphasize that the chosen solutions should be both effective and sustainable and satisfy the long-term environmental and socio-economic objectives of reducing transportation's environmental footprint and improving overall system performance. This approach will continue to be an important tool in making decisions about sustainable development and supporting innovation.

In this research, the FAHP and FTOPSIS techniques have been applied to evaluate the implementation of AI-based eco-driving solutions for sustainable transportation systems in the KSA. The outcome of the FAHP method highlighted that the environmental impact is the first-ranked factor, followed by regulatory compliance and economic viability factors for adopting a green transportation system in the KSA. These results are consistent with those of previous studies, which also underline that environmental, economic, and regulatory compliance are key aspects of sustainable transportation (Aniegbunem & Kraj, 2023; Ho et al., 2015). The sub-factor of air quality improvement was ranked highest due to the impact of eco-driving solutions on air quality improvement. This aligns with the goals of reducing GHG emissions and enhancing public health (Xue et al., 2015). The reduction of carbon emissions was ranked second, showing the significance of tackling climate change. To achieve the same success, the user should be involved in the development of the application. These findings are partially consistent with these previous studies (Ayyildiz et al., 2017; Huang et al., 2018). Furthermore, interfaces also have the ability to optimize the level of compliance with eco-driving guidelines and, therefore, achieve better environmental effects. In addition, successful examples from other countries can further demonstrate that such cooperation may go a long way toward encouraging the adoption of green transportation systems.

The results of the FTOPSIS method showed that smart navigation systems are the first significant AI-based eco-driving solution. These systems apply actual-time information on travel routes, time intervals of non-productiveness, and fuel consumption (Ericsson et al., 2006). Research available to the public has asserted that smart navigation can cut down on time and emissions in equal proportions, as we found about the need for better quality air and minimum carbon emissions. The second key solution is the integration of electric and hybrid vehicles. Upgrading the transport system by incorporating electric and hybrid vehicles is essential to achieve the global goal of low fossil fuel use (Hossain et al., 2022; Waseem et al., 2023). This concurs with the study's observation of economic repercussions for local firms and the decrease in carbon footprint (Zhang et al., 2023). Other studies have shown that hybrid and electric vehicles reduce GHG emissions more than traditional vehicles do (Bai & Liu, 2021; Ercan et al., 2022). In addition, carbon footprint tracking systems have been described as the next important eco-driving solution that can be determined. These systems measure and alert drivers to emissions, providing important statistics for enhancing eco-driving. Automotive technologies play a part in their contributions to carbon emissions reduction and act as key regulatory drivers aiding in formulating or implementing strategies that seek to be environmentally friendly or reduce GHG emissions (Shah et al., 2021).

Another crucial AI-based eco-driving solution is monitoring and improving systems. Constant and regular feedback procedures are mandatory for the constant sustainment and development of eco-driving practices. They enable user feedback, enhance user satisfaction, and ensure compliance with eco-driving guidelines. Intelligent traffic management systems are the least critical eco-driving solution. These systems effectively control traffic flow, resulting in fewer emissions and less congestion. They align with research on infrastructure costs and energy efficiency, as smooth traffic flow consumes less fuel, thereby contributing to improved air quality in the country. Through the management of environmental impact, economic feasibility, user satisfaction, cooperation, and adherence to legal requirements, these solutions can greatly support the country's sustainability agenda. Therefore, the findings are reliable and useful for policymakers as well as stakeholders since they offer a strong foundation on how to adequately deploy and enhance eco-driving technologies.

5.1. Theoretical implications

This research on AI-based eco-driving solutions for the green transport system in Saudi Arabia plays a vital role in the theoretical understanding of sustainable transport systems and environmental management. This research points to the possibility of utilizing AI technologies in the transformation of the transport industry. The AI-based eco-driving solutions prove that vehicle operations can be made effective and environmentally friendly when optimized. This corresponds to the theoretical framework of the positive impacts of AI in the process of attaining SDGs. The combination of FAHP and FTOPSIS methods ensures that transportation planning problems that are multiple and interrelated are effectively solved. Such an approach allows for the evaluation of numerous factors based on value criteria. The focus placed on aspects such as user experience and feedback systems advocates for considering users' insights in developing and deploying eco-driving solutions. This is in line with theories that propose users' involvement in the construction of new transportation systems and urban infrastructure, as it increases the authenticity of users' input with new innovations. The various eco-driving solutions that rely on AI must be implemented through collaboration with different parties, such as central and local governments, AI technology firms, businesses, and legislative bodies. Based on this theoretical framework, this study contributes to the discussion on the need to enhance collaborative governance and public-private relations in order to achieve sustainable transport objectives.

5.2. Practical implications

The policy implications of this study are far-reaching because they provide the necessary guidelines that policymakers and stakeholders in the transport sector can utilize. The results, therefore, provide important directions for KSA policymakers to follow and advise on policy formulations and the green transport sector. With air quality improvement and reduction of carbon emissions ranking high, it also supports the idea that policies should focus on direct solutions to these environmental issues. Moreover, the fact that regulation plays an essential role in controlling economic activity points to the need to formulate and implement high standards of environmental protection regulations. The study also reflects on the feasibility of AI-based eco-driving solutions with positive economic consequences for local stakeholders and overall cost-effectiveness. This means that implementing smart technologies, including electric car charging stations, enhanced traffic systems, and other smart technologies, can provide massive returns in the future. The emphasis on the cost of infrastructure and friendly interfaces also means that investments should be made in technologies that are rational and user-friendly. The relatively high score for educational program effectiveness and the level of awareness of eco-driving measures mean that more focus on public education would serve as the key to eco-driving outcomes. It is also important to note that the study focuses on the need to enhance eco-driving solutions through public-private partnerships. Practical implications include building partnerships between government organizations and companies to promote technological advancements.

6. Conclusions and policy implications

In this study, an investigation on the assessment of factors and AI-based eco-driving solutions for a green transportation system in the KSA, aligning with Visions 2030. Therefore, the FAHP and FTOPSIS model were used to analyze the factors and solutions. The FAHP method showed that environmental factors (C2) play an important role in the efficiency of eco-driving solutions. The results considered improving air quality to be the most essential, due to the current issues of air pollution in urban cities. Emission reductions and energy efficiency are also important to inform the need to reduce carbon emissions in the transport sector as well as optimize energy usage. Another factor critical for the successful deployment of eco-driving solutions is regulatory compliance (C5), which can serve as the foundation. The study focuses on the issues of compliance with local and international environmental practices. This necessitates close collaboration with local and international bodies that regulate the automobile industry, while also addressing legal and ethical concerns related to the outcomes of eco-driving technologies. Besides, economic viability (C1) was found to be the third most important factor and proved that economic feasibility plays a significant role, and there is a special emphasis on the economic effect on business in the KSA.

The findings of the FTOPSIS method indicate that the smart navigation system (ES1) is at the top of the list, showing how real-time information easily translates to a reduction in emissions and improved fuel efficiency. Next, the electric and hybrid vehicle integration (ES3) has been considered as the second key AI-based eco-driving solution. The inclusion of electric and hybrid cars has the added impact of less dependence on conventional fuel sources and decreases GHG emissions. The carbon footprint tracking systems (ES4) were presented as the third important solution. Thus, this study provides a framework for assessing and integrating AI-based eco-driving solutions in the KSA. The research indicates that there should be equal focus on environmental, economic, user, collaborative, and regulatory aspects. Furthermore, the sensitivity analysis not only validates the findings but also demonstrates that the results remain consistent and reliable under varying conditions, thereby confirming their robustness.

6.1. Implications for long-term impacts, scalability, and real-world implementation

This study provides a comprehensive framework for assessing and integrating AI-driven eco-driving solutions to explore the broader implications for achieving Saudi Vision 2030, 2022 goals and aligning with global sustainability frameworks. First, the long-term impact of these solutions extends beyond immediate emission reductions and fuel efficiency improvements, contributing to broader sustainability goals, such as climate change mitigation, urban air quality enhancement, and economic resilience. Over time, the adoption of AI-based eco-driving strategies can lead to systemic transformations in transportation infrastructure, influencing urban planning, investment in green mobility, and shifts in consumer behavior. Second, scalability remains a critical challenge, particularly in ensuring that eco-driving solutions are adaptable across different transport sectors, vehicle types, and geographical regions. The success of large-scale deployment depends on the availability of advanced digital infrastructure, investment in AI-driven mobility systems, and the willingness of both public and private stakeholders to integrate these technologies into existing transport networks. Furthermore, the economic feasibility of scaling up such solutions must be carefully assessed. Finally, real-world implementation also presents several barriers, including technological readiness, regulatory constraints, and user acceptance. AI-driven eco-driving systems require seamless integration with current transport management systems, smart city frameworks, and evolving vehicle technologies. Additionally, regulatory compliance and policy support are essential to facilitate adoption, ensuring alignment with local and international environmental standards. Lastly, behavioral adaptation and public awareness are key to maximizing the effectiveness of these solutions, as user engagement plays a significant role in determining their long-term success.

6.2. Limitations and pathways for future study

The use of AI-based eco-driving solutions relies on the available technology today. For instance, new developments in algorithmic complexity or the incorporation of eco-driving technologies might drastically change the solutions to green transportation systems. We need to conduct more research on user acceptance, usage, and feedback to gather concrete data on the human factors that influence the effectiveness of eco-driving tools. Some enablement strategies can be used, such as surveys, interviews, and focus group discussions with other players in the market. The final drivers connected with economic conditions include the level of oil price volatility, the subsidies to be provided in the region, and the prevailing economic climate in the region that may define or hinder the effectiveness of applying and implementing eco-driving solutions.

It would also be relevant to study the extension of eco-driving solutions with new technologies such as IoT, blockchain, and analytics. They can help in more effectively collecting the data, securing the information, and providing real-time decisions as the eco-driving systems' application makes them more effective and efficient. This is where policy and regulatory environments can present some issues due to their constantly evolving nature. Creating and employing policy simulation models enabled us to estimate the consequences of various policy strategies concerning the adoption and utilization of eco-driving solutions. While FAHP-FTOPSIS provided an optimal balance of accuracy and practicality for this study, future research could compare its performance with other MCDM methods, such as VIKOR, EDAS, MABAC, CODAS, ANP, DEMATEL, and PROMETHEE, to compare these approaches and determine the strengths and weaknesses in the context of eco-driving solution prioritization. This way, the limitations and future research directions can be addressed to better comprehend the effectiveness of AI-based eco-driving solutions and improve the footprint of green transportation systems in Saudi Arabia and other regions of the world.

CRediT authorship contribution statement

Rakan Alyamani: Data curation, Writing – original draft, Conceptualization, Formal analysis. **Yasir Ahmed Solangi:** Project administration, Conceptualization, Writing – original draft, Investigation, Supervision, Funding acquisition. **Muddesar Iqbal:** Writing – original draft, Software, Conceptualization, Resources, Methodology. **Dhafer Almakhles:** Software, Resources, Writing – original draft, Conceptualization. **Cosimo Magazzino:** Visualization, Project administration, Validation, Conceptualization, Writing – review & editing, Supervision.

Data availability statement

Data will be made available at a reasonable request.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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