Automotive Science and Engineering, Vol. 16, No. 3, (2026), 5118-5132

Iran University of Science and Technology

Automotive Science and Engineering

Journal Homepage: ase.iust.ac.ir

ISSN: 2008-9899

A well-to-wheel life cycle assessment of carbon emissions in future driving scenarios revealing interdisciplinary policies for regional sustainable transportation

Shahab Mafi[1], Amirhasan Kakaee[2*], Behrooz Mashhadi[3]

[123] Automotive Engineering Faculty, Iran University of Science and Technology

ARTICLE INFO

Article history:

Received : 17 Oct 2025

Accepted: 26 Jun 2026

Published: 29 Jul 2026

Keywords:

Life cycle assessment

Urban mobility

Sustainable policymaking,

Driving Scenario

Carbon emissions

ABSTRACT

This article introduces a scalable framework based on definition of probable future driving scenarios originated from multidisciplinary policies aimed at transport sustainability. The generation of realistic driving cycles based on recorded real microtrips is used for simulation of carbon emissions in future driving scenarios defined by target characteristic parameters. The suggested framework identifies possible contradicting multidisciplinary policies, highlighting the interdisciplinary requirement of policies for sustainable transportation in well-to-wheel life cycle. Battery electric vehicles were found to be unsustainable in regions with less than 30% share of renewable sources in electric grid, but substantial 25% reduction of carbon emissions is achieved with 50% share of renewables. The stability of clean power generation with different environmental conditions is highlighted. Emerging low carbon fuels, sustainable urbanization and less intensive driving habits would keep internal combustion engines as a dominant powertrain of choice in future fleets of private vehicles.

1. Introduction

Well-to-wheel (WTW) life cycle assessment (LCA) of carbon emissions in vehicles is a standardized methodology that quantifies the environmental impacts of vehicles from energy and material production (well-to-tank, WTT) to operation (tank-to-wheel, TTW), focusing on energy consumption and greenhouse gas emissions.

Despite advancements in WTW LCA, a significant research gap exists in integrating realistic driving cycles tailored to policy-driven traffic scenarios and local energy grid characteristics. Existing studies often rely on standardized driving cycles like New European Driving Cycle (NEDC), or Worldwide Harmonized Light Vehicles Test Cycle (WLTC) for TTW or use phase impact that may not reflect real-world conditions, particularly in congested urban areas like Tehran, leading to inaccuracies in emission evaluations in local settings [1]. Challenges such as driving data quality and characteristic parameters selection further limit LCA accuracy when local conditions are being studied [2].

This study addresses the present gaps by developing an LCA framework based on recorded real local driving data for generation of realistic local driving cycles based on pre-specified driving scenarios. A driving scenario is combination of traffic conditions defined by characteristic parameters. The scenario-based microtrips model or SBM developed in this research enhances local LCA studies by providing a data-driven and scalable solution for quantification of local conditions including traffic conditions and fuel or

*Corresponding Author
Email Address: kakaee_ah@iust.ac.ir
https://doi.org/10.22068/ase.2026.739

energy supply pathways. The SBM's scalability allows researchers to adjust parameters for various purposes, such as emission analysis or policy evaluation in different regions with various conditions and traffic congestions.

Applied to context of Iran, this research quantifies the WTW environmental impact of regional powertrain technologies available for passenger vehicles under different driving scenarios influenced by local transport or city planning policies. Life cycle analysis of carbon emissions or carbon footprint is then used to evaluate the sustainability of different policies for sustainable policymaking. The proposed framework aims to:

1. Develop a model for generating realistic driving cycles applicable to diverse local contexts
2. Quantify the WTW carbon emissions of different vehicle types in variable driving scenarios
3. Evaluate different policies and provide scalable regional solutions for transport sustainability

Consequently, the developed framework offers actionable insights for sustainable urban mobility in local context, by emphasizing the importance of local well-to-wheel LCA studies.

1.1. Tank-to-Wheel Life Cycle Assessment of Powertrain Technologies

The use-phase impacts under different driving conditions have been one of the main research areas in life cycle assessment studies of different powertrain technologies. The large impact of urban driving on increased energy consumption of different passenger vehicle platforms has been highlighted by past literature with 10-25% increase reported in urban driving cycles [3], [4]. These findings are not limited to passenger vehicles and increase in energy use for public vehicles driving in congested urban areas has been recorded as well [5], [6].

The increase of energy consumption and emissions in local traffic conditions compared with standard regulatory driving cycles like NEDC and WLTC has led to a growing gap between real-driving emissions and those reported by regulatory bodies for type-approval of passenger vehicles, indicating value of local traffic conditions in evaluation of energy consumption and emission levels of passenger vehicles [1], [7]. Despite introduction of real driving emission (RDE) protocols and portable emissions measurement systems (PEMS) to measure real-driving emissions, integration of RDE into standard regulatory frameworks remains limited due to associated costs and validity of recorded data according to regulation requirements and local road networks [8], [9]. Consequently, regulators in less developed countries like Iran still rely on standard driving cycles that do not reflect the randomness inherent in real-world driving due to complication with RDE and PEMS integration in type-approval tests.

Syntetic driving cycles have been used for better representation of local driving and generation of realistic driving cycles based on real driving data is widely studied in previous literature through methods ranging from k-means clustering [10], Markov chains [11] and neural networks with varying results depending on local traffic conditions [12], [13]. Driving categorizations based on different characteristic parameters of local driving conditions has also shown good representation of real driving through segregation of different driving scenarios [2], [14]. These findings highlight the possibility of replacing RDE through careful generation of synthetic driving cycles based on recorded real driving data [1], [15].

Dynamic vehicle models have been established as an alternative to PEMS by showing good accuracy in simulation of vehicle performance and emissions in a driving cycle. Coupled with synthetic driving cycles, the computational speed and accuracy of CAE methods proves beneficial for tank-to-wheel emission analysis of vehicle fleets in large datasets of realistic generated driving cycles with less deviation from real-world emissions [1], [16].

Powertrain technologies are considered as main contributors to TTW emissions, but unsustainable policies or aggressive driving behaviors greatly influence sustainability of different powertrains in real driving or TTW phase [17], [18]. These findings highlight the multidisciplinary nature of emission mitigation activities in different regions [19], [20].

1.2. Well-to-Tank Life Cycle Assessment of Powertrain Technologies

Investigation of carbon footprint can be categorized in three different levels depending on the depth of investigation required by researcher. These categories for transport sector are summarized as direct, indirect controllable and indirect uncontrollable emissions. Indirect emissions are less emphasized in LCA literature due to complexity and vague definition and some researchers only consider tailpipe emissions in

[DOI: 10.22068/ase.2026.739]

consideration of carbon footprint in transport sector [21], [22]. Despite zero tailpipe emissions of battery electric vehicles (BEVs), battery manufacturing, charging, degradation and recycling are challenges with specific carbon emissions that are not present in internal combustion engine vehicles [23], [24].

Indirect controllable emissions including fuel or electricity production and distribution have massive contribution in total life cycle emissions of vehicles [25], [26]. Additionally, vehicle manufacturing, maintenance and end-of-life recycling are sources of indirect carbon emissions with latter being investigated heavily in recent literature [27], [28]. Indirect emissions are more profound in fossil-heavy energy grids like Iran where burning fossil fuels is still the dominant form of energy generation despite development plans for sustainable electricity generation [29], [30].

Consequently, the consideration of indirect controllable emissions is vital in determination of carbon footprint of transport sector in local contexts. Energy grid efficiency, sensitivity to battery size and diminishing returns in fossil-heavy grids all contribute to increase in total carbon footprint of alternative vehicle powertrains [4], [31].

Emerging low-carbon or sustainable fuels for internal combustion engines is an area of research where a research gap exists. Insufficient focus on fuel production processes for sustainable fuels emphasizes the need for comprehensive LCA evaluations to assess the true environmental impact of sustainable fuels in internal combustion engines [3].

1.3. Research Contribution and LCA in Iran

The LCA studies in the context of transport sector in Iran has been mainly focused on tailpipe emissions of passenger vehicles, neglecting well-to-tank phase due to limited data on indirect carbon emissions associated with energy supply chains [6], [32]. Recent studies on alternative fuels have contributed to more accurate life cycle assessments of different energy pathways available for transport sector in Iran [33], [34]. Efficiency improvements of local electric grid have also been investigated more recently, leading to better understanding of WTT emissions [35], [36].

A significant research gap exists in sustainability analysis of passenger vehicles in different traffic conditions. The sensitivity of use-phase impacts to driving conditions particularly in congested urban areas and influence of urbanization policies on traffic conditions coupled with dependency of energy generation to fossil fuels signals for a interdisciplinary approach in policymaking to achieve any lasting sustainability in transport sector in Iran or similar regions.

Foundations laid in this research enables comprehensive assessment of WTT and TTW carbon emissions for passenger or public vehicle fleets by using real driving data for generation of realistic driving cycles in accordance with traffic conditions influenced by transportation or city planning policy. Generation of realistic driving cycles is essential for reflection of transient, random nature of real driving causing divergence between real and regulatory driving cycles.

2. Methodology of Suggested LCA Framework

The following section discusses the suggested LCA framework visualized in Figure 1. The Scenario-Based Microtrips model or SBM generated realistic driving cycles based on recorded real driving data. Additionally, the framework includes dynamic vehicle simulation of generated driving cycles for TTW emissions and available local energy grid data for WTT emissions.

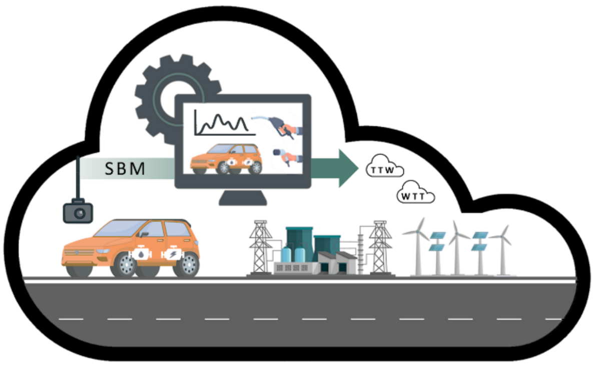

Figure 1: LCA framework based on real driving data, SBM, dynamic vehicle simulation and local energy grid data

2.1. The Scenario-Based Microtrip Model

Life cycle assessment of carbon emissions in vehicle fleets should consider the randomness and changeable traffic conditions present in real driving. Reflection of changeable traffic conditions influenced by transport or urbanization policies in generated driving cycles is the core reason for development of scenario-based microtrips model or SBM. Integration of SBM with LCA framework contributes to flexibility of

[DOI: 10.22068/ase.2026.739]

suggested framework in assessment of carbon emissions in different driving scenarios.

2.1.1. Driving Data Recording

The quality and scale of recorded real driving data ensure the validity of future driving scenarios with reflection of new driving conditions in generated driving cycles, requiring large fleet of vehicles and drivers in addition to extensive data collection in all possible road types.

Figure 2 shows frequency of collected data in different districts of Tehran which includes various road types and driving scenarios particularly in downtown areas with older road infrastructure.

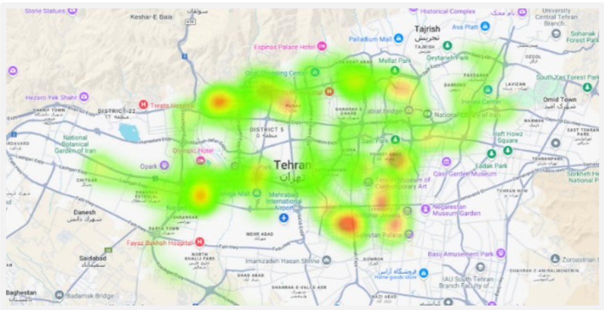

Figure 2: Collected driving data density in Tehran

Approximately 50,000 kilometers or 1460 hours of driving data from passenger sedan vehicles with were collected in span of a year between 2023 to 2024. The drivers were notified of data collection and were not limited in driving styles or destinations. Table 1 displays general information regarding recorded real driving data in Tehran.

The data loss often seen in GPS data collection because of signal loss is mitigated with on-board data recording devices capable of recording parameters including vehicle speed, engine speed, throttle opening, fuel consumption rate, accelerator pedal and brake pedal inputs. High rate of data recording at 3Hz, eliminates big acceleration spikes due to recording inconsistencies as data is interpolated at fixed rate of 1Hz for driving cycle generation.

Table 1: General information of collected real driving data in Tehran

	Average Duration (s)	Average Distance (km)	Average Driving Speed (km/h)	Average Positive Acceleration ($\frac{m}{s^2}$)	Average Negative Acceleration ($\frac{m}{s^2}$)
Real Drive	**1670**	**16.2**	**41**	**0.5**	**-0.54**

2.1.2. Driving Scenario Determination

For transport research purposes, a driving scenario is described as representation of different driving conditions in a driving cycle, leading to different values of characteristic parameters like average driving speed.

The determination of driving scenarios in this research is based on mapping average driving speed and speed-acceleration product per driving distances according to equations (1) to (3). The driving scenario defines average speed ($\bar{v}$), as indication of traffic conditions, and cumulative speed-acceleration product ($\overline{SA}$), as indication of driving behavior or intensity of driving cycles per driving distances shorter than target distance or S_j.

$$\boldsymbol{S_j = \{v_k, a_k \mid distance < target\}} \quad (1)$$

$$\boldsymbol{\bar{v}_j = \frac{1}{n_j}\sum_{v\in S_j} v} \quad (2)$$

$$\boldsymbol{\overline{SA}_j = \frac{1}{n_j}\sum_{v,a\in S_j} v.a^{+}} \quad (3)$$

The current driving scenario of recorded real driving data for 20-kilometer driving distances is displayed in Figure 3 reflecting average change of traffic conditions present in a real drive. The speed increases in the first 5 kilometers indicating tendency of real driving towards rural and motorway conditions. Driving speed is then reduced towards end of driving cycles as fleet is reaching destinations often located in downtown areas with more congested urban driving. The cumulative nature of speed-acceleration product or SA as characteristics parameter identifies instances of aggressive driving with sharp inclinations resulting in higher total SA or more intensive driving cycle.

[DOI: 10.22068/ase.2026.739]

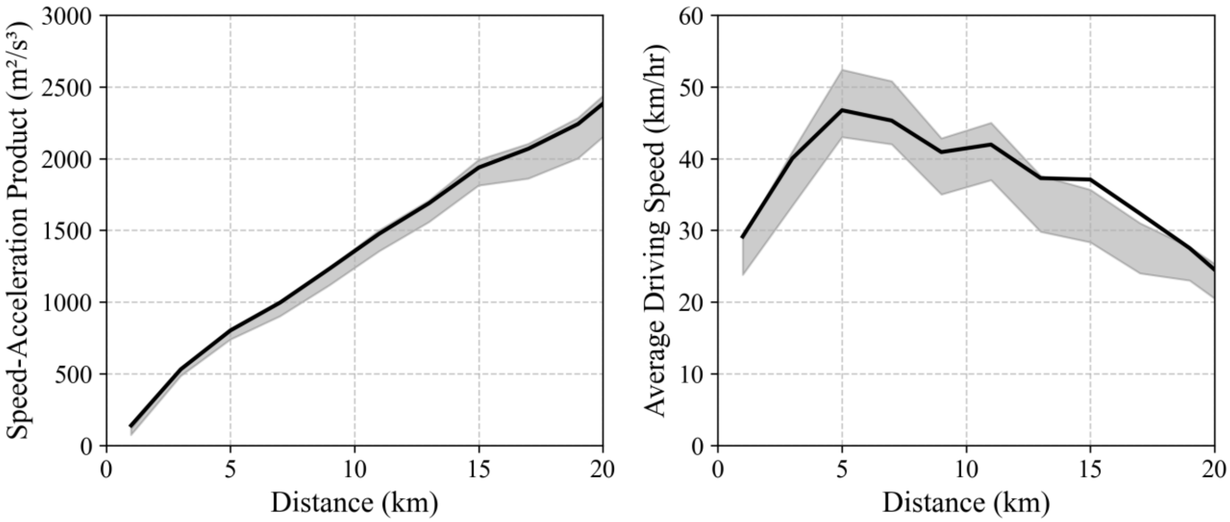

Figure 3: The current driving scenario based on speed-acceleration product (left) and average driving speed (right)

The dependency of driving scenarios to travelled distance captures true dynamics of real driving including average road types used in a real drive with same target distance. With this definition of driving scenarios, the impact of sustainable transport and urbanization policies leading to a change in driving conditions, like less congested urban driving by using an overpass in the place of a junction, will be better realized and reflected in generated driving cycles.

The choice of characteristic parameters in definition of driving scenario should ultimately be based on high correlation of characteristic parameters to target parameter identified for the research based on feature selection methods like principal component analysis or PCA but inclusion of general parameters like speed and acceleration could lead to better generalization of driving cycles.

2.1.3. Realistic Driving Cycle Generation

The scenario-based microtrips model or SBM developed in this article introduces an iterative method for generation of driving cycles based on definition of main characteristic parameters. As stated in previous section, the driving scenario is specified as average driving speed and speed-acceleration product throughout the travelled distance in driving cycle. The iterative process of SBM shown in Figure 4 begins with a random selection of a microtrip, followed by selection of subsequent microtrips based on driving scenario until target distance is reached. The random selection of the first microtrip is done irrespective of driving scenario to better represent the randomness of real driving. Following microtrips are then selected based on remaining distance to target and permissible characteristic parameters (CPs) range. The integrated fallback mechanism allows temporary deviation of characteristic parameters from target driving scenario to improve generalization of SBM while studying driving scenarios with low microtrip occurrence in real data.

2.2. Carbon Footprint Evaluation

In this research, the total carbon emissions of well-to-wheel or WTW phase are called carbon footprint. The carbon footprint (CF) is calculated by adding direct and indirect carbon emissions in well-to-tank and tank-to-wheel phases according to Equation 4.

$$CF_{WTW} = [DoD \times E_{bat} \times k_e]_{BEV} + [m_f \times LHV_f \times k_f]_{ICEV,HEV} + CO_{2_{TTW}} \quad \textbf{(4)}$$

[DOI: 10.22068/ase.2026.739]

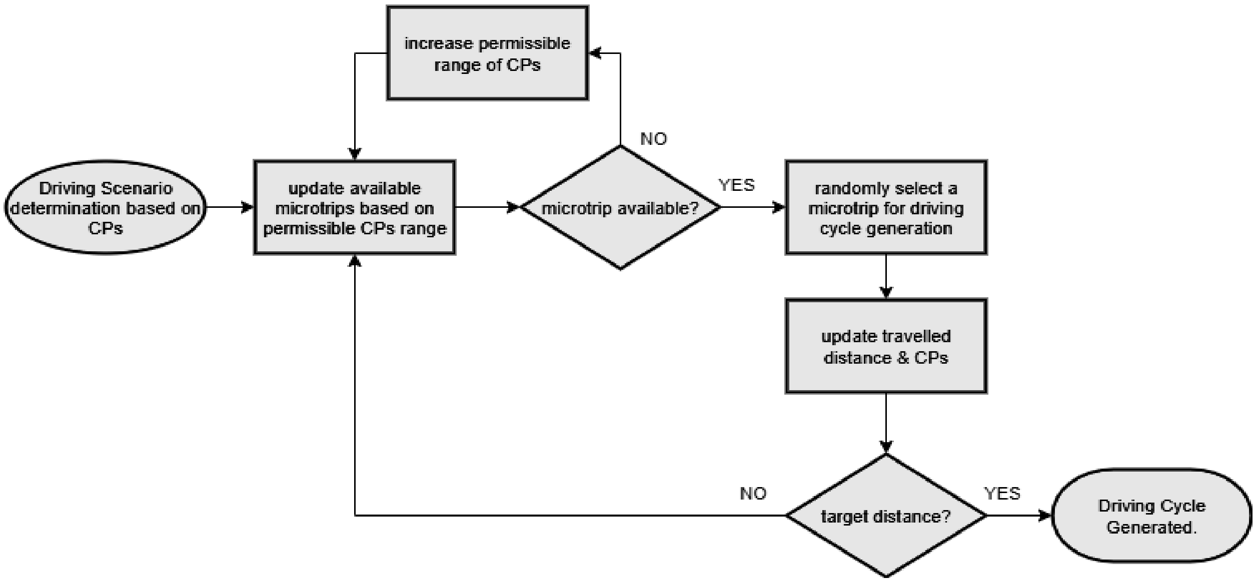

Figure 4: The flowchart of SBM model for generation of driving cycles based on pre-specified driving scenarios

The carbon emissions of driving or $CO_{2_{TTW}}$ is calculated from dynamic simulation of selected vehicles, with technical specifications detailed in

Table 2, validated with real carbon emissions [1]. The WTT carbon emissions are correlated with local energy grid mix and supply chains which are often impacted by changeable environmental conditions like ambient temperature. Therefore, the conversion factors k_f and k_e are estimated from previous studies on the subject [29], [30].

Mass of burned fuel, m_f, low heating value of fuel, LHV_f, depth of discharge for battery, DoD, and capacity of fully charged battery pack, E_{bat}, are required variables for life cycle assessment of carbon emissions, or carbon footprint, for selected vehicles.

3. Results and Discussion

Determination of driving scenarios for life cycle assessment of selected vehicles in Tehran is done by assignment of different characteristic parameters per different travelled distance for each driving scenario to reflect different driving conditions in generated driving cycles.

Definition of target driving distance for future driving scenarios is based on knowledge of local traffic and driving conditions. In this article, authors decided to set slightly longer target driving distance compared to average driving in Tehran. The real driving scenario of Tehran, displayed in Figure 3, shows increase of average driving speed replicating motorway driving just after driving distance is travelled. This highlights the absence of motorway road types in an average daily drive or heavy congestions in motorway roads, preventing vehicles to reach motorway-level speeds.

Table 2: Technical Specifications of selected vehicles for dynamic simulation

	ICEV	HEV	BEV
Total Vehicle Mass	1500 kg	1700 kg	1750 kg
Engine Displacement	1658 cc	1658 cc	-
Rated Power & Torque	100 kW – 160 Nm	100 kW – 160 Nm 30 kW – 165 Nm	200 kW – 420 Nm
Fuel Type	Gasoline - CNG	Gasoline - CNG	-
Battery Capacity	-	9 kWh	80 kWh

[DOI: 10.22068/ase.2026.739]

In this article, SCN0 indicates current driving scenario determined from real driving data for selected travelled distance. SCN1 corresponds to optimal interdisciplinary policies resulting in noteworthy increase of average driving speed like improved public transport, more accessible highway networks or better traffic management in congested downtown area. On the other hand, SCN2 is the worst-case scenario of business-as-usual policies in Tehran like inadequate and old public transport system, uncontrolled growth in passenger vehicle uses and poor urbanization plans resulting in more congested urban driving.

In addition to policies influencing traffic conditions, forecasted driving scenarios influenced by social and educational policies promoting less aggressive driving habits are presented as SCN3 and SCN4. SCN3 represents disregard of driving habit correction policies resulting in more aggressive driving. On the contrary, SCN4 is representation of less aggressive driving.

Figure 5 displays selected transport policies through mean value of characteristic parameters, average driving speed and speed-acceleration product, per travelled distance for 20-kilometer driving cycles showcasing the capability of SBM in discrimination of different driving scenarios. Total of 100 realistic driving cycles were generated for each driving scenario based on real recorded microtrips. Table 3 compares average values of main variables for generated driving cycles for each driving scenario.

3.1. Investigation of new conditions in future driving scenarios

Traffic conditions are often categorized as urban, rural and motorway conditions distinguished by driving speed. In this article and based on local driving conditions in Tehran, instances of driving with low speed (v<35 km/hr) is considered urban driving. On the other hand, motorway driving is categorized by high-speed driving (v>70 km/hr) and rural driving represents the intermediate driving speed range. The corresponding change of traffic conditions in generated cycles of each driving scenario is displayed in Table 4 based on urban, rural and motorway driving. The average idle duration of each scenario is direct reflection of new driving conditions. In urban-oriented driving scenarios like SCN2, longer idle durations would be natural outcome of more congested urban driving. Different average idle durations for other driving scenarios including high-speed driving scenario with more motorway-oriented driving is deemed not significant and within normal range of variation for idle duration.

Definition of new driving scenarios for better representation of new driving conditions is an important milestone in investigation of WTW carbon emissions in future driving scenarios. Local experience or comprehensive real data recording is highly recommended for more accurate forecasting of future driving scenarios.

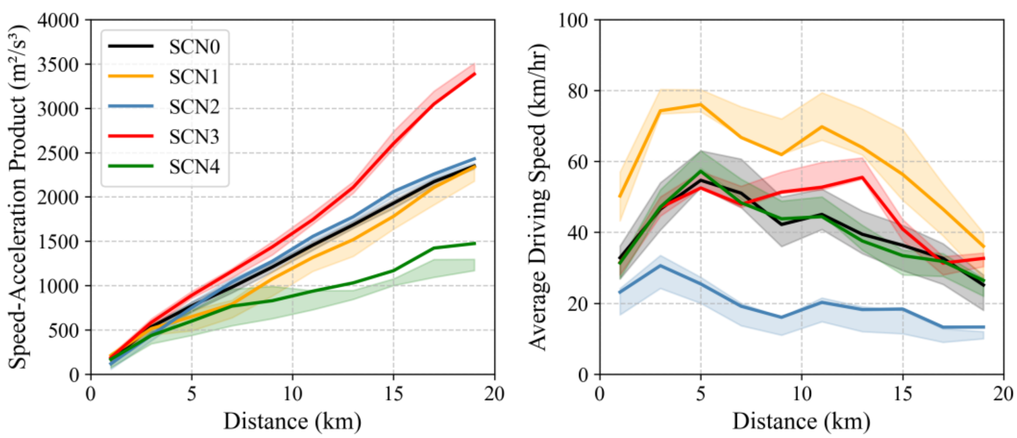

Figure 5: Definition of driving scenarios based on SA (left) and average driving speed (right) per travelled distance

[DOI: 10.22068/ase.2026.739]

Table 3: General information of generated driving scenarios

Driving Scenario	Average Duration (s)	Average Distance (km)	Average Speed (km/h)	Average Positive Acceleration $(\frac{m}{s^2})$	Average Negative Acceleration $(\frac{m}{s^2})$
SCN0	1970	19.4	39	0.47	-0.52
SCN1	1264	19.4	59	0.48	-0.57
SCN2	4512	19.6	19	0.46	-0.48
SCN3	1814	19.8	42	0.55	-0.60
SCN4	2138	19.5	39	0.40	-0.45

Table 4: Selected transport policies and their impact on target traffic scenario

Name	Description	Urban (%)	Rural (%)	Motor way (%)	Average Idle Duration (s)
SCN 0	Current Driving Scenario	**22**	**60**	**18**	**180**
SCN 1	High-Speed Driving Scenario	**7**	**35**	**58**	**65**
SCN 2	Low-Speed Driving Scenario	**70**	**29**	**1**	**683**
SCN 3	Aggressive Driving Scenario	**20**	**59**	**21**	**127**
SCN 4	Eco Driving Scenario	**22**	**63**	**15**	**310**

3.2. Life cycle assessment of carbon footprint in future driving scenarios

The future driving scenarios selected for this article are presented to quantify the carbon emissions in various scenarios and driving conditions for investigation of more sustainable policies. The sensitivity of carbon emissions to driving scenarios is displayed in Figure 6. BEVs do not show particular sensitivity to changing driving scenarios. On the other hand, internal combustion engines have higher sensitivity to changing conditions making ICEVs and HEVs particularly sensitive to traffic conditions.

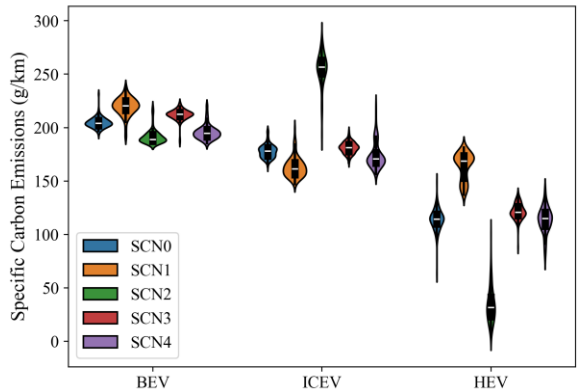

Figure 6: Distribution of well-to-wheel carbon emissions of selected vehicles in different driving scenarios

Distribution analysis of carbon footprint for selected vehicles in different driving scenarios highlights the consideration of future driving scenarios for fleets vehicle selections. In other words, transport sustainability is not only limited to sustainable vehicular design choices like electrification or hybridization, but sustainable urbanization and social policies should also be investigated for a passenger vehicles fleet with mixed vehicle types as well.

Figure 7 displays tank-to-wheel and well-to-wheel specific carbon emissions of each vehicle type and average specific carbon emissions, or carbon footprint, of each driving scenario.

Despite zero carbon emissions in tank-to-wheel or driving phase, fossil-heavy electric grid in Iran completely diminishes the sustainability of BEVs in well-to-wheel scope. In fact, BEVs should not be considered as sustainable option of transport sector for passenger vehicles in Tehran unless the share of renewable sources in energy generation of electric grid is increased up to 30%.

Total carbon footprint of selected vehicles in WTW is displayed again in Figure 8 with assumption of substantial increase in renewable

[DOI: 10.22068/ase.2026.739]

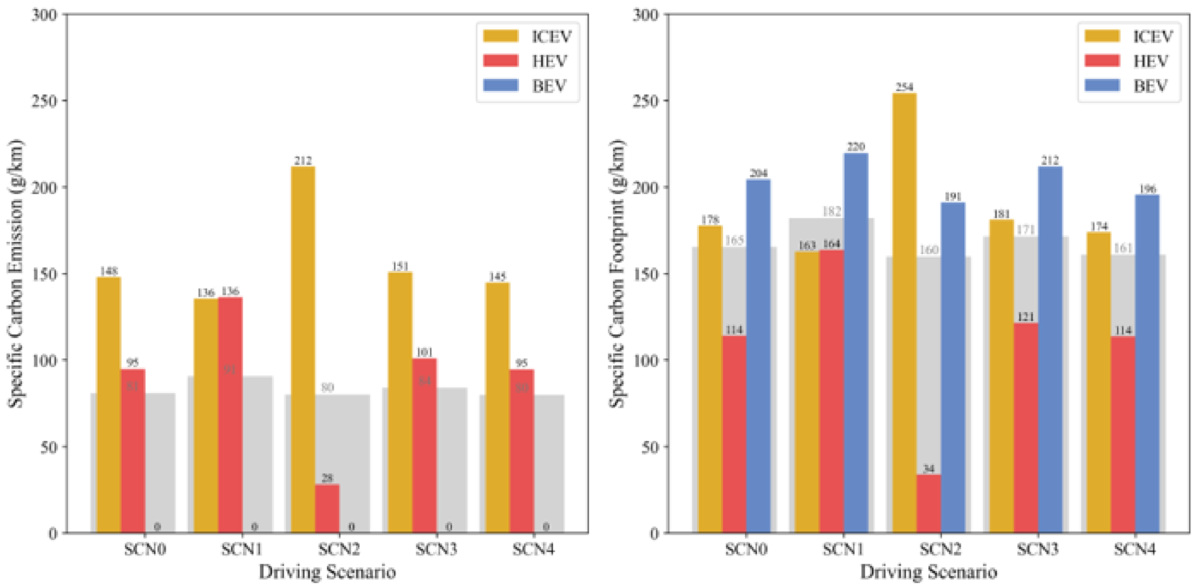

Figure 7: The average tank-to-wheel (left), well-to-wheel (right) and average total carbon emissions of selected vehicles in different driving scenarios

energy use, reducing total carbon footprint of BEVs towards better sustainability compared to ICEVs in all driving scenarios regardless of any change in traffic conditions or driving behavior. Increasing renewable energies share to 50% would make BEVs more sustainable option compared to HEVs in all but driving scenario SCN2 with more congested urban driving and longer driving durations, effectively offsetting the previously considered benefits of BEVs in longer idle durations with more auxiliary power consumption for cabin and battery cooling.

Switching to HEVs as vehicle of choice for passenger vehicles fleet in Tehran would immediately cut TTW carbon emissions by up to 30% in current driving scenario and up to 80% in heavily congested urban driving or SCN2. Despite BEVs, integration of HEVs into vehicle fleets require no additional infrastructure, thus making HEV adoption an easy solution for more sustainable transportation but urbanization policies toward higher average driving speeds, SCN1, would negate HEVs advantage over ICEVs. Heavier vehicle platforms and tendency of hybrid energy management strategies in selecting combustion engine as primary traction source in high vehicle speeds are primary reasons of high carbon emissions in motorway-oriented future driving scenarios.

The above examples highlight the challenges in policymaking regarding sustainable transportation in passenger vehicles fleets and demonstrate the interdisciplinary nature of policies required for consideration in local context to achieve sustainable transportation in regional level.

3.3. Sustainable regional fleet vehicle mix

The variable carbon footprint sensitivity of different vehicle types to future driving scenarios requires interdisciplinary decisions for optimal sustainability of transport sector. For example, in the context of regions with heavy reliance of electric grid to fossil fuels like Tehran, BEVs were found to be sustainable only by substantial increase in electricity generation with renewable sources requiring heavy investments in infrastructure and revision of regional power generation outlooks. These findings are scalable to other vehicle types capable of recharging from the electric grids like PHEVs. On the other hand, despite generally better sustainability of HEVs compared to ICEVs, the carbon reduction targets of HEV adoption would not be fully gained if sustainable

[DOI: 10.22068/ase.2026.739]

urbanization and city planning policies resulting in higher average driving speed and less travel durations come into effect.

A concept of optimum fleet vehicle mix is defined for improved transport sustainability in regions with multiple dominant driving scenarios or conflicting interdisciplinary sustainable policies like promotion of HEVs while moving toward higher average driving speed or SCN1. Equation 5 is used to optimize w_j for each target vehicle types in the fleet by minimizing $\overline{CF}_{Total,WTW}$ or mean carbon footprint of combined driving scenarios. Subsequently, $\overline{CF}_{ij}$ denotes mean carbon footprint of a specific vehicle type j in scenario i.

$$\sum_{j=1}^{n} w_j \overline{CF}_{ij} \leq \overline{CF}_{Total,WTW} \qquad (5)$$

Optimization of vehicle fleet mix including ICEVs, HEVs and BEVs for Tehran based on WTW life cycle carbon footprint assessment was done for determination of sustainable vehicle type shares in case any of the studied future driving scenarios occur. The sustainable solutions are provided for different share of renewable energies in electric grid and displayed in Table 5.

Optimization of fleet mix as sustainable solution in case any of the studied future driving scenarios occur indicates total domination of BEVs as sustainable vehicle choice with only 30% increase of renewable energy sources in power generation as opposed to required 50% increase for making BEVs a sustainable choice in all future driving scenarios in case of equal vehicle type shares. Domination of vehicle fleet with BEVs in case of 50% increase in renewable energies would result in 24% decrease of total average carbon footprint in all driving scenarios.

3.4. Challenges regarding regional sustainable policies for transport sector

Consideration of carbon emissions in manufacturing and end-of-use phase could present different sustainable solutions regarding minimization of total carbon footprint in a fleet. The battery recycling in HEVs and BEVs, not considered due to complexities and lack of data on end-of-use carbon emissions in regional level, is found to be a significant source of carbon emissions for these types of vehicles.

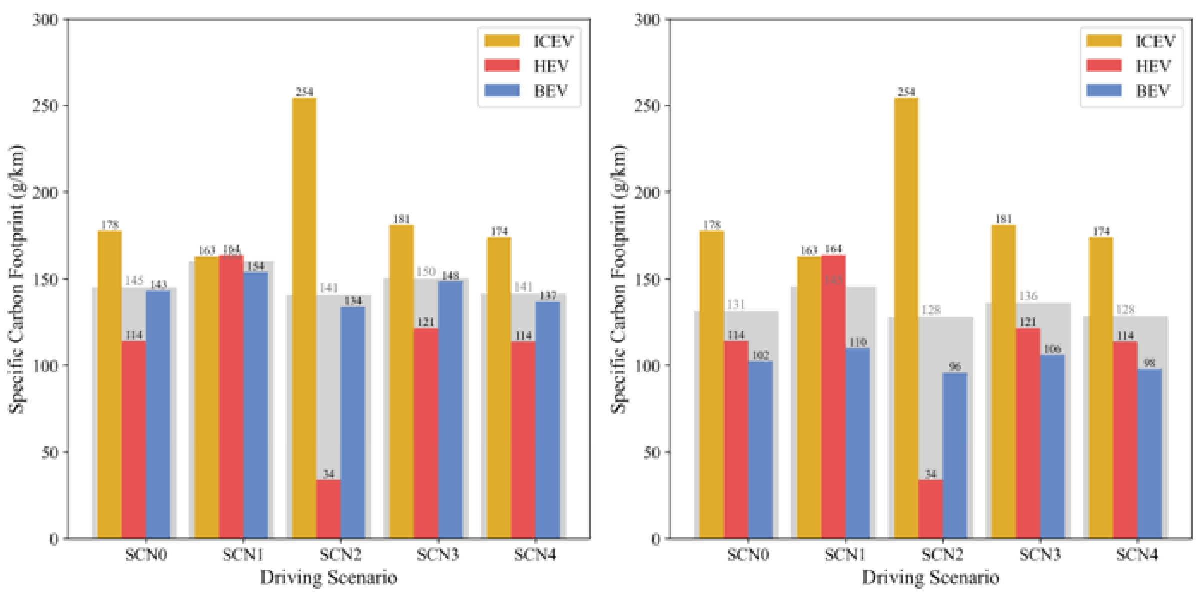

Figure 8: The average WTW total carbon footprint of selected vehicles in different driving scenarios with increased share of renewable energies to 30% (left) and 50% (right) in electric gird

[DOI: 10.22068/ase.2026.739]

Table 5: Sustainable vehicle type share for all future driving scenario

Renewables share in electric grid	$\overline{CF}_{Total,WTW}$ before (g/km)	Vehicle Type Share (%)			$\overline{CF}_{Total,WTW}$ after (g/km)
		ICEV	**HEV**	**BEV**	
0 %	**168**	**60**	**40**	**0**	**157 (-6.5 %)**
15 %	**158**	**60**	**40**	**0**	**157 (-0.6 %)**
30 %	**147**	**0**	**0**	**100**	**143 (-2.7 %)**
50 %	**134**	**0**	**0**	**100**	**102 (-24 %)**

Optimization of recycling process and utilization of more sustainable materials in manufacturing of vehicles and batteries improves the sustainability of vehicles. This further validates the interdisciplinary nature of sustainability in transport sector and how fleet choices must be taken with consideration of carbon footprint in life cycle of vehicles.

4. Limitations of current study

Investigation of changeable local conditions and their impact on fuel supply chain or electricity generation should also be investigated to portray a full picture of environmental impact associated with transport sector in a local context. Stable power generation efficiency is crucial for any sustainable policy in future. This is even more profound with integration of renewable energy sources in electric grid as they are more reliable on environmental conditions like weather for sustainable power generation.

The role of vehicle ageing including powertrain and battery degradation on lifecycle specific carbon emissions is highly dependent on environmental conditions and driving parameters. Future works must study these mechanisms under varying driving conditions for a parametric solution to estimation of deterioration factors, applicable to different driving and vehicle conditions.

The fleet optimization in this work is purely environmental and restricted to carbon emissions and social or economic costs are not considered. Further research on impacts of transport modes on different sectors is required for national fleet mix optimization.

5. Conclusions and final remarks

This article presented a robust framework for life cycle assessment of carbon emissions in future driving scenarios to evaluate the sustainability of interdisciplinary policies with impact on transport sector. The well-to-wheel scope has been chosen to consider indirect carbon emissions regarding electricity generation and fuel supply chains, consequently resulting in carbon footprint of selected vehicle types in selected driving scenarios based on real driving data.

Results highlighted how best available pathways in terms of sustainability must be investigated in regional context with consideration of local conditions like traffic flow, driving habits and energy supply grids. In other words, not only sustainability solutions have to be considered in multidisciplinary context, but they should be tailored to the specific region as well.

Based on investigation of carbon footprint in Tehran, BEVs are not a viable sustainable transportation option unless more than 30% of power generation in well-to-tank phase is with renewable sources instead of total reliance on fossil fuels. Increasing renewables share to 50% would yield 24% reduction in total carbon footprint when passenger vehicle fleet is all BEVs.

Self-charging hybrids not dependent on electric grid for charging are more sustainable than ICEVs for passenger vehicles in Tehran but more efficient sizing or energy control strategies is required in future driving scenarios with higher average driving speeds to keep HEVs a sustainable solution in future of Tehran as urbanization policies tend to lessen the traffic congestion and increase the average driving speeds.

The outcome of social policies for improving driving habits has been studied through investigation of future driving scenario with different average accelerations. Although not as severe as traffic conditions, promotion of smooth driving is recommended as sustainable solution.

Optimization of vehicle type mix in passenger fleet further validated the viability of internal combustion engines as a sustainable mode of transportation in case of fossil-heavy electric grid. The combined fleet of ICEVs and HEVs with optimized share of vehicle types is capable of about 6% reduction in total carbon footprint irrespective of driving scenario. Switching to low carbon fuels like compressed natural gas (CNG) and hydrogen as primary energy source for internal combustion engines is highly recommended for substantial decrease in greenhouse gas emissions.

CNG is already presented as a fuel option for passenger vehicles in Iran but improvements to infrastructure is needed for more fleet penetration compared to gasoline. More research on optimized blends, fuel production, scalability and integration with different generations of internal combustion engines is recommended for achieving sustainability with lower well-to-wheel costs.

The LCA framework proposed in this research provides a hindsight into future carbon footprint based on sustainability assessment of multidisciplinary policies and the possible resulting future scenarios. Authors suggest utilization of AI in determination of different characteristics parameters and other regions for scalability analysis of the LCA framework provided in this article.

6. Acknowledgment

Authors would like to acknowledge Iran Khodro Powertrain Company (IPCO) for design and installation of the onboard recording device used for recording real driving data.

References

[1] S. Mafi, A. Kakaee, B. Mashadi, A. Moosavian, S. Abdolmaleki, and M. Rezaei, “Developing local driving cycle for accurate vehicular COinf2/inf monitoring: A case study of Tehran,” J Clean Prod, vol. 336, 2022, doi: 10.1016/j.jclepro.2021.130176.

[2] J. I. Huertas, L. F. Quirama, M. Giraldo, and J. Díaz, “Main characteristic parameters to describe driving patterns and construct driving cycles,” Transp Res D Transp Environ, vol. 114, p. 103570, 2023, doi: 10.1016/j.trd.2022.103570.

[3] H. Liu, S. Yu, T. Wang, J. Li, and Y. Wang, “A systematic review on sustainability assessment of internal combustion engines,” J Clean Prod, vol. 451, p. 141996, Apr. 2024, doi: 10.1016/j.jclepro.2024.141996.

[4] C. Bauer, J. Hofer, H.-J. Althaus, A. Del Duce, and A. Simons, “The Environmental Performance of Current and Future Passenger Vehicles: Life Cycle Assessment of Electric, Hybrid, and Fuel Cell Vehicles,” Appl Energy, vol. 266, p. 115013, 2020, doi: 10.1016/j.apenergy.2020.115013.

[5] K. Pietrzak, O. Pietrzak, and A. Montwiłł, “Life Cycle Assessment Study on Public Transport Bus Fleet Electrification as a Contribution to the Sustainable Transport System Development in a City,” Science of The Total Environment, vol. 816, p. 151513, 2022, doi: 10.1016/j.scitotenv.2022.151513.

[6] E. Heidari, S. Bikdeli, and M. R. Mansouri Daneshvar, “A dynamic model for CO2 emissions induced by urban transportation during 2005–2030, a case study of Mashhad, Iran,” Environ Dev Sustain, vol. 25, no. 5, pp. 4217–4236, May 2023, doi: 10.1007/s10668-022-02240-7.

[DOI: 10.22068/ase.2026.739]

[7] Jan Dornoff Victor Valverde Morales Uwe Tietge, "On the way to 'real-world' CO2 values? The European passenger car market after 5 years of WLTP," 2024. [Online]. Available: https://theicct.org/publication/real-world-co2-emission-values-vehicles-europe-jan24/

[8] J. Claßen, S. Krysmon, F. Dorscheidt, S. Sterlepper, and S. Pischinger, "Real Driving Emission Calibration—Review of Current Validation Methods against the Background of Future Emission Legislation," Applied Sciences, vol. 11, no. 12, p. 5429, Jan. 2021, doi: 10.3390/app11125429.

[9] Y. Wang et al., "Impact of altitude on the real driving emission (RDE) results calculated in accordance to moving averaging window (MAW) method," Fuel, vol. 277, p. 117929, Oct. 2020, doi: 10.1016/j.fuel.2020.117929.

[10] M. Azadi, S. Dezianian, A. Navi, A. Salmani, T. Gharaati, and A. Faraji, "Development of a Driving Cycle Based on Data Recorded from an Electric-Gasoline Hybrid Vehicle on Two Routes in Tehran City with K-means Algorithm," Karafan Quarterly Scientific Journal, vol. 19, no. 1, pp. 629–653, 2022, doi: 10.48301/kssa.2022.315133.1840.

[11] J. D. K. Bishop and C. J. Axon, "Using natural driving experiments and Markov chains to develop realistic driving cycles," Transp Res D Transp Environ, vol. 137, p. 104507, Dec. 2024, doi: 10.1016/j.trd.2024.104507.

[12] A. Gebisa, G. Gebresenbet, R. Gopal, and R. B. Nallamothu, "A Neural Network and Principal Component Analysis Approach to Develop a Real-Time Driving Cycle in an Urban Environment: The Case of Addis Ababa, Ethiopia," Sustainability, vol. 14, no. 21, 2022, doi: 10.3390/su142113772.

[13] J. Topić, B. Škugor, and J. Deur, "Neural Network-Based Prediction of Vehicle Fuel Consumption Based on Driving Cycle Data," Sustainability 2022, Vol. 14, Page 744, vol. 14, no. 2, p. 744, Jan. 2022, doi: 10.3390/SU14020744.

[14] L. F. Quirama, M. Giraldo, J. I. Huertas, and M. Jaller, "Driving cycles that reproduce driving patterns, energy consumptions and tailpipe emissions," Transp Res D Transp Environ, vol. 82, p. 102294, 2020, doi: https://doi.org/10.1016/j.trd.2020.102294.

[15] J. Claßen et al., "RDE cycle generation – a statistical approach to cut down testing effort and provide a secure base to approve RDE legislation compliance," in Internationaler Motorenkongress 2019, J. Liebl, C. Beidl, and W. Maus, Eds., Wiesbaden: Springer Fachmedien, 2019, pp. 37–56. doi: 10.1007/978-3-658-26528-1_3.

[16] R. J. Gräbe and J. W. Joubert, "Are we getting vehicle emissions estimation right?," Transp Res D Transp Environ, vol. 112, p. 103477, Nov. 2022, doi: 10.1016/j.trd.2022.103477.

[17] O. Ghaffarpasand, M. R. Talaie, H. Ahmadikia, A. TalaieKhozani, M. D. Shalamzari, and S. Majidi, "How does unsustainable urbanization affect driving behavior and vehicular emissions? Evidence from Iran," Sustain Cities Soc, vol. 72, p. 103065, Sep. 2021, doi: 10.1016/J.SCS.2021.103065.

[18] H. Lei, S. Zeng, A. Namaiti, and J. Zeng, "The Impacts of Road Traffic on Urban Carbon Emissions and the Corresponding Planning Strategies," Land 2023, Vol. 12, Page 800, vol. 12, no. 4, p. 800, Mar. 2023, doi: 10.3390/LAND12040800.

[19] S. Jia, L. Bi, W. Zhu, and T. Fang, "System dynamics modeling for improving the policy effect of traffic energy consumption and CO2 emissions," Sustain Cities Soc, vol. 90, Mar. 2023, doi: 10.1016/j.scs.2023.104398.

[20] K. Wu et al., "Big-data empowered traffic signal control could reduce urban carbon emission," Nature Communications , vol. 16, no.

[DOI: 10.22068/ase.2026.739]

1, pp. 1–12, Dec. 2025, doi: 10.1038/S41467-025-56701-4;TECHMETA=119,129,141;SUBJMETA=4066,4081,682,704,706,844;KWRD=CLIMATE-CHANGE+MITIGATION,ENERGY+AND+SOCIETY,ENVIRONMENTAL+IMPACT.

[21] D. Pandey, M. Agrawal, and J. S. Pandey, "Carbon footprint: Current methods of estimation," Environ Monit Assess, vol. 178, no. 1–4, pp. 135–160, Jul. 2011, doi: 10.1007/S10661-010-1678-Y/METRICS.

[22] P. Fernandes, E. Ferreira, E. Macedo, and M. C. Coelho, "Unraveling roundabout dynamics: Analysis of driving behavior, vehicle performance, and exhaust emissions," Transp Res D Transp Environ, vol. 133, Aug. 2024, doi: 10.1016/j.trd.2024.104308.

[23] T. Cotterman, E. R. H. Fuchs, K. S. Whitefoot, and C. Combemale, "The transition to electrified vehicles: Evaluating the labor demand of manufacturing conventional versus battery electric vehicle powertrains," Energy Policy, vol. 188, p. 114064, May 2024, doi: 10.1016/j.enpol.2024.114064.

[24] M. H. Nahani, G. R. Molaeimanesh, and M. Dahmardeh, "Evaluating the Performance and Environmental Impact of Electric Vehicles with Old Battery Pack: A Well-to-Wheel Analysis," ASE, vol. 14, no. 4, pp. 4541 EP – 4549, Dec. 2024, doi: 10.22068/ase.2024.683.

[25] J. Morfeldt, S. Davidsson Kurland, and D. J. A. Johansson, "Carbon footprint impacts of banning cars with internal combustion engines," Transp Res D Transp Environ, vol. 95, p. 102807, Jun. 2021, doi: 10.1016/J.TRD.2021.102807.

[26] M. V. Chester and A. Horvath, "Environmental assessment of passenger transportation should include infrastructure and supply chains," Environmental Research Letters, vol. 4, no. 2, p. 024008, 2009, doi: 10.1088/1748-9326/4/2/024008.

[27] X. Xia and P. Li, "A Review of the Life Cycle Assessment of Electric Vehicles: Considering the Influence of Batteries," Science of The Total Environment, vol. 814, p. 152870, 2022, doi: 10.1016/j.scitotenv.2021.152870.

[28] J. F. Peters and M. Dorsch, "A Review of Life Cycle Assessment Studies of Electric Vehicles with a Focus on Resource Use," Resources, vol. 9, no. 3, p. 32, 2020, doi: 10.3390/resources9030032.

[29] M. Peyvandi, A. Hajinezhad, and S. F. Moosavian, "Investigating the intensity of GHG emissions from electricity production in Iran using renewable sources," Results in Engineering, vol. 17, p. 100819, 2023, doi: https://doi.org/10.1016/j.rineng.2022.100819.

[30] F. Dalir, M. S. Motlagh, and K. Ashrafi, "A dynamic quasi comprehensive model for determining the carbon footprint of fossil fuel electricity: A case study of Iran," J Clean Prod, vol. 188, pp. 362–370, 2018, doi: https://doi.org/10.1016/j.jclepro.2018.03.274.

[31] Y. Wang, D. Hu, Q. Ma, and Y. Zhao, "Life Cycle Assessment of Plug-In Hybrid Electric Vehicles Considering Different Vehicle Working Conditions and Future Development Trends," Energies (Basel), vol. 17, no. 17, p. 4283, 2024, doi: 10.3390/en17174283.

[32] M. M. Estalki and A. A. Orkomi, "Assessing on-road emission inventory and compatible control measures for morning rush hour in Rasht, Iran: 2030 perspective," International Journal of Environmental Science and Technology, vol. 21, no. 9, pp. 6481–6498, May 2024, doi: 10.1007/s13762-024-05483-1.

[33] L. Fayazi Rad, M. Amini, A. Ahmadi, and S. Hoseinzadeh, "Environmental and Economic Assessments of Hydrogen Utilization in the Transportation Sector of Iran," Chem Eng Technol, vol. 46, no. 3, pp. 435–446, 2023, doi: 10.1002/ceat.202100500.

[34] S. M. Hosseini, A. Ardehali, and H. Yousefi, "From waste to wheel: Comparative

life cycle assessment of sustainable bio-CNG pathways for Tehran's public transport," Process Safety and Environmental Protection, vol. 197, p. 107071, May 2025, doi: 10.1016/j.psep.2025.107071.

[35] H. Yousefi, R. Habibifar, A. Farhadi, and S. M. Hosseini, "Integrated energy, cost, and environmental life cycle analysis of electricity generation and supply in Tehran, Iran," Sustain Cities Soc, vol. 97, p. 104748, 2023, doi: https://doi.org/10.1016/j.scs.2023.104748.

[36] S. A. Modirzadeh et al., "Potentials of greenhouse gas emission reduction through energy efficiency improvement in Iran's petrochemical sector," Energy, vol. 311, p. 133297, Dec. 2024, doi: 10.1016/j.energy.2024.133297.

[DOI: 10.22068/ase.2026.739]