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Is the Corporate Average Fuel Economy Scheme Effective at Improving Vehicle Fuel Efficiency in a Small-Scale Market? Evidence from Taiwan

Hwa Lin [1,2,*], Yun-Hsun Huang [1] and Jung-Hua Wu [1]

[1] Department of Resources Engineering, National Cheng Kung University, Tainan 701, Taiwan; z10808014@email.ncku.edu.tw (Y.-H.H.); hwaa@mail.ncku.edu.tw (J.-H.W.)
[2] Mechanical and Mechatronics Systems Research Laboratories, Industrial Technology Research Institute, Hsinchu 310, Taiwan
* Correspondence: vera.lin@itri.org.tw; Tel.: +886-3-5919317

Abstract: This article discusses how the introduction of corporate average fuel economy (CAFE) standards in Taiwan, whose market and industry size are much smaller than those of Europe, the United States, Japan, and China, can effectively improve vehicle energy efficiency. It examines the changes in passenger car energy efficiency under Taiwan's CAFE framework and evaluates CAFE compliance performance to summarize its impacts and challenges. Observations indicate that the strategically flexible CAFE scheme is indeed more effective than mandatory minimum energy performance standards (MEPS) in encouraging manufacturers to comply through various methods. This approach has ultimately increased the overall average fuel efficiency of Taiwan's passenger cars by 23.5% since 2012, while maintaining the diversity of vehicle models in the market. However, there are challenges to implementing CAFE in a small market, such as difficulties in introducing and promoting high-efficiency models, limited activity in the CAFE credit market, and the current overly favorable policy design. The design of the CAFE mechanism is crucial not only for benchmarking with larger economies but also for taking into account local market conditions and industrial capabilities. Taiwan's next phase of CAFE must incorporate multi-dimensional adjustments to achieve higher, potentially net-zero vehicle efficiency targets.

Keywords: vehicle fuel efficiency; corporate average fuel economy; small-scale market

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1. Introduction

The global vehicle fuel efficiency management system originated in the United States. In 1978, the U.S. federal government enacted the Energy Policy and Conservation Act, which established the corporate average fuel economy (CAFE) standard to improve the average fuel economy of cars and light trucks [1]. Subsequently, major automotive industry regions and countries, such as the European Union, Japan, and China, adopted the concept of corporate-level management for vehicle fuel efficiency or CO_2 emissions regulations and have continued to achieve positive results [2–5]. The progressive tightening of fuel economy standards since the adoption of these mechanisms has generally been associated with improvements in fuel efficiency. However, the impact of these regulations varies by region, and none have shown a consistently upward trend [6]. Furthermore, annual improvements in vehicle fuel economy have been more pronounced in countries where regulations and/or incentives have been implemented [7].

The CAFE standard functions as a corporate-level management mechanism. This framework evaluates manufacturers based on the average fuel efficiency of their entire fleet, allowing them to strategize and make trade-offs between different models to meet regulatory standards [8]. Such an approach provides manufacturers with the flexibility to

achieve compliance by considering their entire fleet rather than focusing solely on individual models [9–11]. CAFE calculates the harmonic average efficiency of the vehicle models sold by each manufacturer and compares it to a corporate-level target value determined in a similar manner. CAFE does not directly incentivize consumers to choose fuel-efficient vehicles, nor does it directly affect fuel prices. Instead, it attempts to increase the cost to automakers of selling inefficient vehicles by introducing both restrictions and flexibility measures [8,12]. These measures enable each manufacturer to achieve compliance in various ways depending on its product characteristics and operational strategies, thereby indirectly improving overall vehicle efficiency [13].

The CAFE management system in the U.S. sets vehicle efficiency standards while providing complementary measures to facilitate implementation by manufacturers, including credit systems for carry-forward, credit transfers, credit trading, and technical credits (e.g., incentive multipliers and off-cycle credits) [14,15]. This credit system allows automakers to earn credits for exceeding fuel economy standards in a given year, which can then be used to offset deficits in subsequent years (carry-forward) or previous years (carry-back). Credit trading offers a market-based alternative to fines, providing an additional revenue stream for manufacturers that consistently meet standards. Credits can also be used to reduce the costs associated with the introduction of new high-efficiency models or as a buffer to manage compliance.

Off-cycle credits and other technical incentives further motivate the advancement of vehicle energy-saving technologies by rewarding automakers for innovations that enhance real-world fuel economy but are not captured in traditional test cycles.

The CAFE mechanism provides an incentive for vehicle manufacturers to improve the fuel efficiency of vehicles by fostering innovations that align with regulatory goals. Consumers are not directly involved in this process; however, they benefit from lower fuel costs and reduced environmental impact. These efforts also contribute to broader societal goals, such as enhancing energy security and reducing greenhouse gas emissions [3,16].

Taiwan is a mountainous island with a dense population concentrated in a narrow band along its eastern coast. The fact that roughly 97% of Taiwan's energy needs are met by imports has prompted the government to implement policies promoting energy conservation. Throughout the island, road transportation is the primary mode of travel. Despite the development of good public transportation systems, such as MRT and buses, in major cities (e.g., Taipei and Kaohsiung), the enormous number of private cars and motorcycles has led to urban traffic congestion and air pollution.

At the end of 2023, the population of Taiwan was 23 million, and the number of passenger cars was 7.3 million, which is equivalent to 1 car for every 3.15 people. There are also 14.55 million motorcycles and scooters registered for the road, which means that nearly every adult over the age of 20 owns at least one of these vehicles [17]. Each year, roughly 300,000 new passenger cars are sold in Taiwan, most of which are Japanese brands (e.g., Toyota, Nissan, and Honda), due in part to local contract manufacturing in Taiwan.

Taiwan's automotive industry plays a crucial role in the global supply chain, particularly in the production of automotive components and electronic parts. Taiwan's domestic passenger car market is relatively small, but it enjoys a significant competitive edge over other countries in the manufacture of automotive parts. Active investment in the EV sector by Taiwanese companies, such as Foxconn (Hon Hai Precision Industry Co., New Taipei City, Taiwan), has further bolstered Taiwan's position in the global automotive supply chain [18].

Since 1988, Taiwan has regulated vehicle energy use by enforcing the minimum energy performance standards (MEPS), which set minimum threshold standards. This regulatory approach affects approximately 300,000 passenger vehicles annually, prohibiting the sale or importation of vehicles that do not meet MEPS standards [19].

To improve energy efficiency in response to global climate change trends, Taiwan adopted the CAFE scheme in 2017, based on practices in countries such as the United States, Europe, and Japan. While the CAFE system has been in place for many years in

countries and economies with large automotive industries and consumer markets, Taiwan has a relatively small consumer market and limited research and development capabilities within its domestic automotive industry, with vehicle model development often relying heavily on technical support from parent companies [18]. Therefore, whether from the perspective of market size or automotive industry conditions, Taiwan's environment differs significantly from the large-scale markets where CAFE is typically applied.

Previous research on the economics of vehicle fuel efficiency can be categorized into econometric estimation and economic modeling. The former examines historical vehicle fuel efficiency data and the socioeconomic impact of efficiency standards, while the latter uses models to simulate the effects of changes in fuel efficiency standards (or penalties) on manufacturer decisions [9]. Much of the research in this field addresses the effects of regulations, subsidies, fluctuations in fuel prices or taxes, and vehicle attributes on vehicle energy efficiency [20,21]. In Europe and Japan, the impact of efficiency standards on the fuel consumption of new vehicles is more pronounced than the effect of rising fuel prices [22].

Most of the qualitative research on regulating vehicle energy efficiency has focused on policy implementation outcomes in countries involved in large-scale vehicle manufacturing, such as the United States, the European Union, and China. This focus is likely due to the political significance of these issues and the availability of data [7]. The lack of qualitative research on vehicle energy efficiency in smaller markets can likely be attributed to the absence of robust regulatory systems, the non-disclosure of vehicle energy efficiency or CO_2 data by governments, or the scarcity of academic studies focusing on these regions. As a result, countries and territories such as Taiwan are rarely included in comparative studies on the regulation of vehicle energy efficiency.

This is the first paper to introduce the CAFE framework adopted in Taiwan for vehicle energy efficiency management. We employ a qualitative analysis approach to explore the differences between Taiwan's vehicle energy efficiency policies and the CAFE standards implemented in larger vehicle-manufacturing countries. We also examine the relationship between the CAFE framework and vehicle energy efficiency in Taiwan. While the qualitative nature of this study provides valuable insights into the regulatory landscape, it cannot quantify the direct impact of incentive multipliers on the CAFE framework, which limits the ability to measure the effectiveness of the policy in precise numerical terms. Despite these limitations, this study provides valuable initial insights into the regulatory environment for vehicle energy efficiency in Taiwan and provides a basis for future quantitative studies that could more rigorously evaluate the impact of the CAFE framework.

This paper offers qualitative insights into the challenges of implementing the CAFE system and its impact on vehicle fuel efficiency. Our analysis covers the CAFE scheme adopted by Taiwan, compliance with CAFE standards, and subsequent trends in vehicle fuel efficiency. Finally, we examine the implementation of a corporate management scheme to enhance vehicle energy efficiency in small-scale markets, such as Taiwan.

2. The CAFE Framework in Taiwan

Since 1988, the Energy Administration of Taiwan has been the regulatory body overseeing the implementation of Minimum Energy Performance Standards (MEPS) for newly sold fuel-powered passenger cars, light trucks, and motorcycles under the Energy Administration Act. The MEPS sets the minimum energy efficiency thresholds that new vehicle models must meet, based on engine displacement and vehicle type. These standards are considered relatively undemanding, as their primary purpose is to prevent the entry of highly inefficient vehicles into the market.

Nonetheless, the MEPS for passenger cars underwent "standard tightening" three times between 1989 and 2009, during which time this was the primary tool for improving vehicle energy efficiency.

In response to global trends such as climate change, energy scarcity, high international oil prices, and demands for greenhouse gas reduction, the Taiwanese government introduced the CAFE system in 2017. This marked a significant milestone in the manage-

ment of vehicle energy efficiency in Taiwan, which has evolved into a two-tier system. The first tier requires vehicles to meet the MEPS for their model types, determining their eligibility for sale. The second tier sets corporate-level fuel economy targets through the CAFE mechanism.

Taiwan's CAFE framework aligns with practices in Europe, the United States, Japan, and China, establishing more stringent standards than the MEPS. It primarily targets larger manufacturers to meet national average fuel economy goals. In the first phase of implementing CAFE standards for Taiwan, the objective was to achieve a 15% improvement in passenger car fuel efficiency compared to 2009, with a compliance target of 14.5 km/L. In 2022, the second phase (CAFE II) was introduced to align with international greenhouse gas reduction goals, setting a more ambitious target of 20 km/L. CAFE II required improvements in the efficiency of gasoline and diesel engines and promoted the development and sale of electric, hybrid, and plug-in hybrid vehicles. It also incorporated international practices, such as sales incentive multipliers and eco-innovation technology credits to enhance vehicle energy efficiency in Taiwan.

In Taiwan's CAFE mechanism, the calculation formulas for the corporate sales-weighted average energy efficiency and the corporate sales-weighted average energy efficiency target are defined by Equations (1) and (2), respectively:

$$CAFE_{Avg_{FE}} = \frac{\sum_1^j V_j \times W_j}{\sum_1^j \frac{V_j}{FE_j}} \quad (1)$$

where:

$CAFE_{Avg_{FE}}$: corporate sales-weighted average energy efficiency;
j: the j-th vehicle model manufactured or imported by the automaker;
FE_j: fuel economy of the j-th vehicle model (km/L);
V_j: sales volume of the j-th vehicle model;
W_j: incentive multiplier for the j-th vehicle model.

$$CAFE_{Avg_T} = \frac{\sum_1^j V_j}{\sum_1^j \frac{V_j}{T_j}} \quad (2)$$

where:

$CAFE_{Avg_T}$: corporate sales-weighted average energy efficiency target;
j: the j-th vehicle model manufactured or imported by the automaker;
T_j: CAFE standard of the j-th model.
V_j: sales volume of the j-th vehicle model.

The fuel efficiency of vehicles under Taiwan's CAFE framework is evaluated according to the testing procedures prescribed by the European Directive 1999/100/EC and its subsequent amendments, using the new European driving cycle (NEDC). Until 2020, manufacturers could opt to test using either the NEDC or the worldwide harmonized light vehicles test cycle (WLTC) while adhering to the same standard values. Table 1 outlines the tiered CAFE standards for each phase, which are applied based on the reference weight of each vehicle model.

Table 1. Taiwan's Phase I and Phase II CAFE standards.

Reference Weight (kg)	CAFE I Standard (km/L)	CAFE II Standard (km/L)
RW $\leq$ 850	19.2	23.3
850 < RW $\leq$ 965	18.2	23.3
965 < RW $\leq$ 1080	17.4	23.3
1080 < RW $\leq$ 1190	16.6	22.2
1190 < RW $\leq$ 1305	15.6	21.3
1305 < RW $\leq$ 1420	15	20.4
1420 < RW $\leq$ 1530	14.1	19.6
1530 < RW $\leq$ 1640	13.3	18.9
1640 < RW $\leq$ 1760	12.5	18.2
1760 < RW $\leq$ 1870	11.8	17.5
1870 < RW $\leq$ 1980	11.2	16.9
1980 < RW $\leq$ 2100	10.5	16.1
2100 < RW $\leq$ 2210	9.7	15.6
2210 < RW $\leq$ 2380	9.3	15.2
2380 < RW $\leq$ 2610	8.4	14.3
2610 < RW	7.2	13.7

Source: Taiwan's Energy Administration, Ministry of Economic Affairs [19].

As shown in Table 2, the CAFE mechanism in Taiwan includes a credit system and incentives applicable only to manufacturers with an annual sales volume of at least 100 units or total sales exceeding NTD100 million (approximately USD 3.1 million). Manufacturers can carry forward positive credits for up to four years. Non-compliant manufacturers can meet their annual requirements by transferring credits from other manufacturers. The price of traded credits is determined by market mechanisms, without government regulation.

Table 2. Taiwan's CAFE mechanism.

Component	Description
Regulation Type	Annual/Real-time
Credit carry-forward	Positive credits remaining after the annual settlement can be banked and used within four years following the settlement year.
Credit transfer/Credit trading	If non-compliant after the annual settlement, manufacturers can transfer equivalent credits from other manufacturers to meet compliance requirements.
Eco-innovation Credit	Effective from 1 January 2022, if a vehicle manufacturer develops an eco-innovation technology or a product with proven energy-saving capability that enhances fuel efficiency but does not achieve results in driving cycle tests, the central competent authority may approve a specific credit value. This credit can then be added to the company's corporate sales-weighted average energy efficiency calculation for the specific model.
Incentive multiplier	Battery electric vehicle (BEV): W = 10 Fuel cell vehicles (FCEV): W = 10 Plug-in hybrid electric vehicle (PHEV) with pure electric travel mileage over 50 km: W = 5 Effective from 1 January 2022, for specific models with fuel efficiency exceeding CAFE standards: 10% over: W = 1.5 20% over: W = 2 30% over: W = 2.5 40% over: W = 3 50% over: W = 3.5
Dispositions	Non-compliant manufacturers will be prohibited from selling vehicle models with fuel economy below CAFE standards after the annual settlement until compliance is achieved.

Source: Taiwan's Energy Administration, Ministry of Economic Affairs [19].

For the incentive measures, the focus is on the setting of the incentive multiplier and its applicable users. During the initial implementation of CAFE, Taiwan was in the early stages of electric vehicle development. As a result, a high multiplier of 10 was set for

electric vehicle sales, allowing manufacturers to count each electric vehicle as 10 units in their fleet average calculations. Early CAFE measures focused primarily on encouraging gasoline and diesel vehicle manufacturers to develop more fuel-efficient models. It was not until the planning of the second phase of CAFE that pure electric vehicle manufacturers were fully integrated into the CAFE framework. CAFE II introduces an incentive multiplier for vehicle models that exceed their CAFE standard by a certain margin. This measure is intended primarily to encourage manufacturers to introduce more efficient hybrid models, especially while the electric vehicle infrastructure remains underdeveloped. The incentive multiplier will play a crucial role in manufacturers' compliance performance and credit balances.

Table 3 summarizes the implementation regulations of countries and territories with large-scale markets applying CAFE standards, as well as Taiwan's regulations. It is evident that although Taiwan's market size is significantly smaller than other countries and territories, it has a strong commitment to vehicle energy management.

Table 3. Comparison of new vehicle market sizes in countries and territories implementing CAFE [17,23–27].

Market	New Passenger Car Market Size	Standard	Management Approach		Structure of Standard
			Corporate-Level Management	Minimum Energy Performance	
United States	14 to 16 million units	Corporate Average Fuel Economy Standards for model years 2027–2031 passenger cars and light trucks	✔		Footprint-based
		Regulations for greenhouse gas emissions from passenger cars and trucks	✔		
European Union	10 to 12 million units	CO_2 emission performance standards for cars and vans (Regulation (EU) 2019/631) [28]	✔		Weight-based
Japan	4 to 5 million units	Act on the Rational Use of EnergyTop Runner Program	✔		Weight-based
South Korea	1.5 to 2 million units	Vehicle Average Fuel Economy and GHG Emission Standards (2021–2030)	✔		Weight-based
China	26 to 28 million units	GB 19578-2021 [29] (per-model standard)		✔	Weight-based
		GB 27999-2019 [30] (corporate average fuel consumption standard)	✔		
Taiwan	0.3 to 0.4 million units	Fuel Economy Standards and Regulations on Vehicle Inspection and Administration [1]	✔	✔	Displacement-based (MEPS) and Weight-based (CAFE)

[1] In "The Fuel Economy Standards and Regulations on Vehicle Inspection and Administration" (MOEAEA, Taiwan), the scope of administration for passenger vehicles includes only sedans and station wagons. Other forms of passenger vehicles, such as vans, are classified as light trucks.

3. Fuel Efficiency Status of Passenger Cars

An analysis of the average fuel efficiency of new vehicles in Taiwan from 2012 to 2023 reveals an average annual sales volume of 294,000 passenger cars, with domestic and imported vehicles roughly equally distributed (Figure 1) [31].

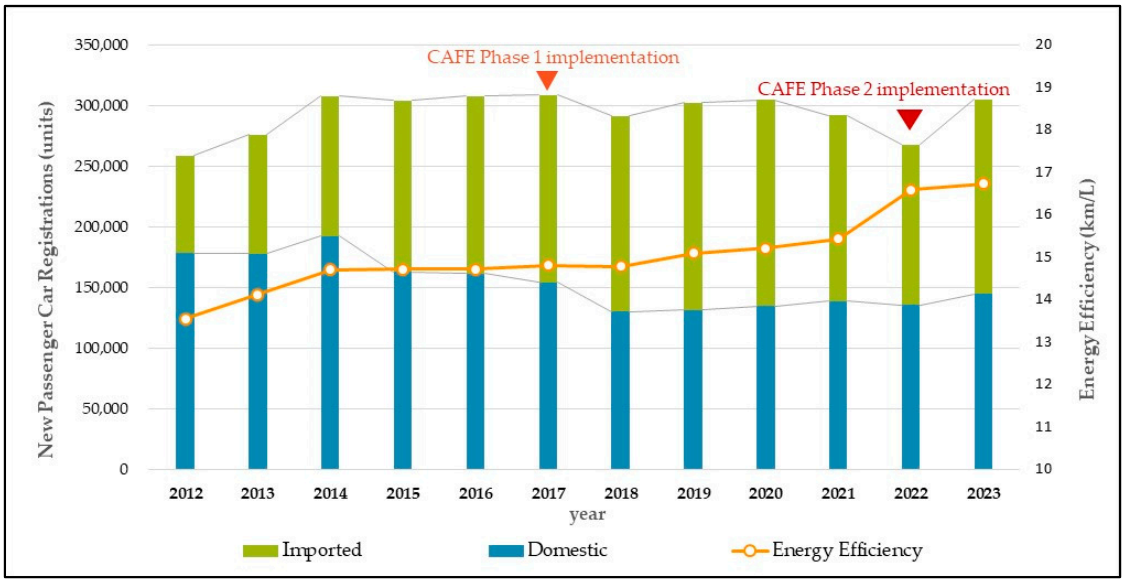

Figure 1. Registration volume and average energy efficiency of new passenger vehicles in Taiwan (2012–2023) [31].

The average annual improvement in vehicle fuel efficiency was roughly 2%. The energy efficiency trend line in Figure 1 shows that the transition from MPES to the CAFE (initial phase) is associated with a slight increase in overall passenger vehicle energy efficiency. Moreover, 2022 marked a turning point between the first and second phases of CAFE, following a 38% tightening of standards with a correspondingly pronounced impact on vehicle energy efficiency.

Using 2012 as the baseline, despite a modest increase in new vehicle sales from 2013 to 2023, overall energy consumption did not increase significantly due to improvements in fuel efficiency. As shown in Figure 2, assuming an annual driving distance of 15,000 km per new passenger car, the number of regulated vehicles in 2023 increased by 26.7% compared to 2012, while overall energy consumption only marginally increased by 2.6%. These findings underscore the substantial impact of energy efficiency improvements on reducing energy consumption in the transportation sector.

The market share and energy efficiency of various powertrain types in Taiwan's new car market from 2012 to 2023 reveal the main trends related to CAFE implementation. (Figure 3). Internal combustion vehicles (ICVs), including gasoline and diesel models, remain dominant. However, diesel passenger cars have maintained a minimal market share, averaging 3.2% over the past 20 years and peaking at just 6.5%. This limited share is largely due to the historical preference in the Taiwanese consumer market for Japanese brands, which focus primarily on developing gasoline and hybrid models. Additionally, the higher costs and environmental concerns associated with diesel vehicles further influence consumer choices. From an efficiency perspective, diesel engines typically outperform gasoline engines under similar conditions due to their higher compression ratios [32,33].

Hybrid electric vehicles (HEVs) have become a well-established energy-saving technology in recent years. The implementation of Taiwan's CAFE I in 2017, followed by the announcement of the second phase in 2018, prompted manufacturers to increase HEV sales in preparation for the 2022 standards. By the end of 2023, HEVs accounted for 24% of the new car market, nearly one-fifth of total sales. This demonstrates a strong correlation between the growth of energy efficiency improvements in non-electric vehicles and the expansion of the HEV market share.

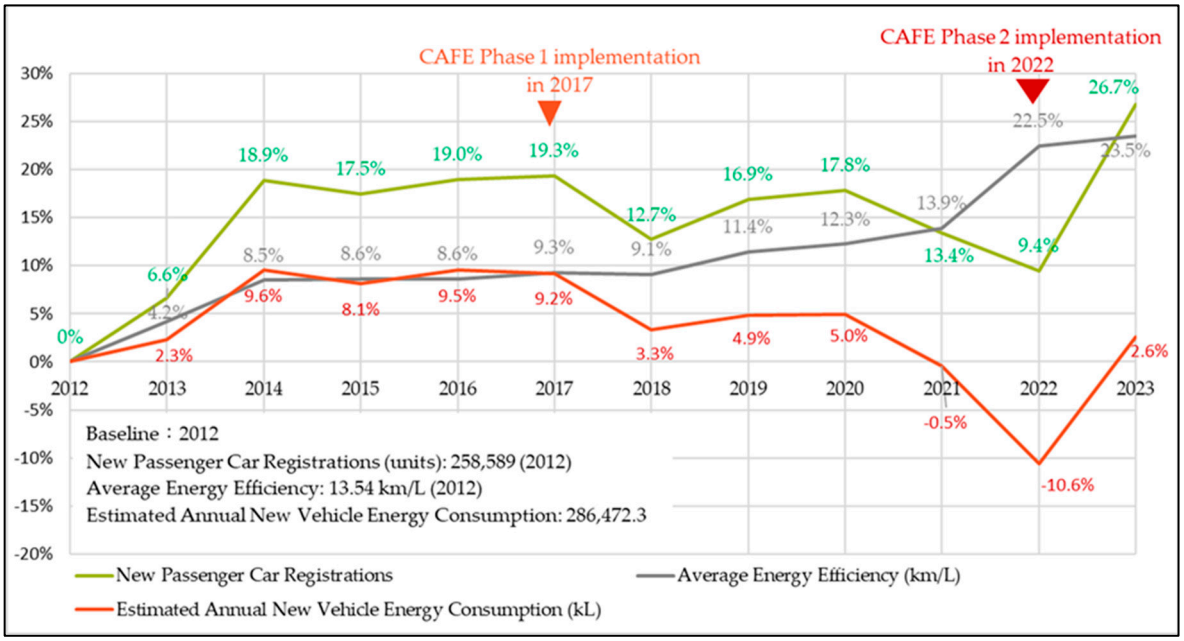

Figure 2. Annual registration volume, average energy efficiency, and annual energy consumption of new passenger vehicles in Taiwan relative to values recorded in 2012.

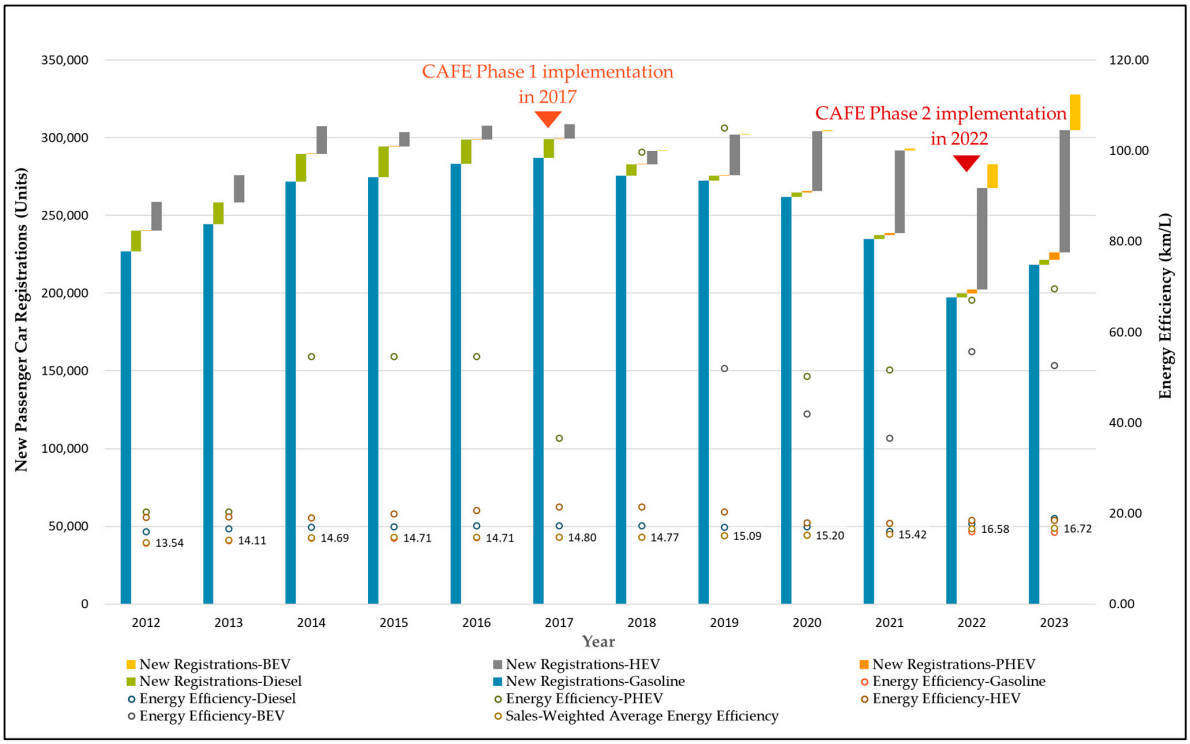

Figure 3. Changes in new passenger vehicle registration volume and energy efficiency as a function of powertrain type for the period 2012–2023.

Plug-in hybrid electric vehicles (PHEVs) are often regarded as a transitional technology toward fully electric vehicles. Equipped with both an internal combustion engine and an electric motor, PHEVs alleviate range anxiety while offering economic benefits by using electricity for most travel [34]. However, early adoption in Taiwan has been hampered by high costs and limited charging infrastructure, keeping their market share below 3%. Recently, the introduction of a diverse range of fully electric vehicle models has intensified

price-performance competition among similar products. Consequently, new PHEV sales have yet to show significant growth.

PHEVs typically operate in two driving modes, one of which is an all-electric mode where the internal combustion engine is not used, similar to fully electric vehicles. When the battery reaches a certain level of depletion, the internal combustion engine is activated and the vehicle transitions to a hybrid mode, similar to an HEV [35]. The energy efficiency of PHEVs has been studied extensively in recent years [36–38] due to the complexity of their systems, which vary widely among manufacturers in terms of power output, battery capacity, and related design aspects. Current testing procedures often fail to accurately reflect the real-world energy efficiency of PHEVs in both fuel and electric modes, as results are typically presented in terms of weighted efficiency (km/L). This can lead to extreme efficiency values, such as claims of over 100 km/L, which do not realistically represent the vehicle's performance in practical driving conditions. Despite these challenges, under the current energy efficiency management framework in Taiwan, PHEV models are still managed based on the efficiency values obtained through standard testing procedures. In practice, when consumers drive PHEVs, the energy efficiency in electric mode can be compared to that of BEVs, while the efficiency in hybrid mode can be compared to that of HEVs.

Battery electric vehicles (BEVs) began to enter Taiwan's passenger car market in limited numbers around 2010. Initially, BEVs were not subject to energy efficiency regulations. However, with the introduction of Taiwan's first phase of CAFE, BEVs were voluntarily included as a compliance incentive for manufacturers. This led to their formal inclusion in the regulated vehicle fleet. BEVs were fully integrated into the energy efficiency management framework with the second phase of CAFE, and by 2023, they accounted for approximately 7% of the market.

The energy efficiency of BEVs is measured in kilometers per kilowatt-hour (km/kWh). To ensure comparability across different fuel types, Taiwan's regulations convert the energy efficiency of electric vehicles to fuel efficiency equivalents (km/L) using a conversion factor set by the Ministry of Economic Affairs (1 L of gasoline is equivalent to 9.07 kWh) [39]. By the end of 2023, 122 BEV models had been certified in Taiwan, with energy efficiencies ranging from 5 to 7.3 km/kWh, equivalent to approximately 45 to 66 km/L.

Over the past decade, significant differences in the energy efficiency performance of various powertrain types have emerged. Using the sales-weighted average efficiency of internal combustion engine vehicles (ICEVs) as a baseline, the efficiency ratios are approximately 1:1.3 for HEVs, 1:3.8 to 1:7.1 for PHEVs, and 1:3.6 for BEVs. These findings, based on standard testing procedures, reflect advances in vehicle energy-saving technologies.

The shift in average fuel efficiency and sales structure suggests that "standard tightening" regulations have effectively improved vehicle efficiency in Taiwan. This is particularly evident with the implementation of CAFE II in 2022, which accelerated the adoption of high-efficiency models (HEVs, PHEVs, and BEVs). As a result, the average fuel efficiency increased from 13.54 km/L in 2012 to 16.58 km/L in 2023, representing a 24% improvement.

4. CAFE Compliance Trends

Figure 4 presents the overall compliance trends under Taiwan's CAFE implementation up to 2023. To analyze the factors influencing these trends, it is essential to deconstruct the principles underlying the CAFE management framework. A manufacturer's compliance at the end of the year is determined by a fixed mathematical formula, as discussed previously. Key parameters influencing compliance include the difference between the energy efficiency of a vehicle model and the applicable CAFE standard, the sales volume of that model, and the applicability of incentive multipliers within the CAFE mechanism.

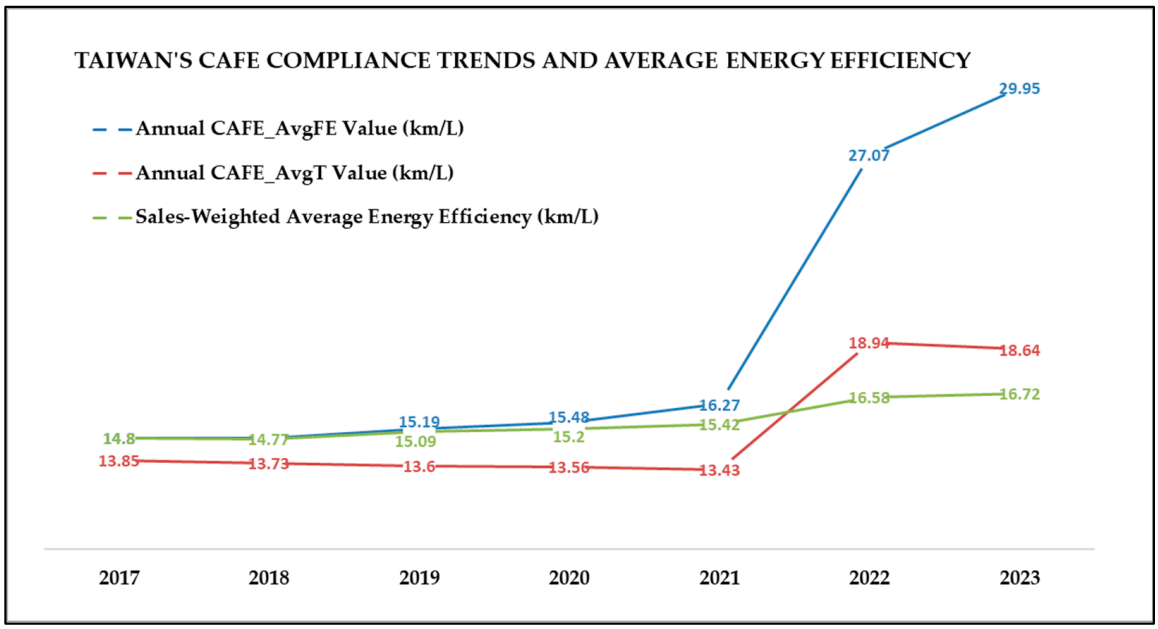

Figure 4. Taiwan's CAFE compliance trends and average energy efficiency (2017–2023).

In this study, "compliance performance" refers to the difference between the average CAFE efficiency value and the required compliance threshold. Without the application of incentive multipliers (Figure 5), PHEVs may have higher compliance performance than BEVs, primarily due to the specific calculation methods used for PHEV efficiency under standard testing procedures. However, when incentive multipliers are applied, the pre-existing efficiency gaps between HEVs, BEVs, and PHEVs are amplified, resulting in greater disparities in compliance performance (Figure 6). Conversely, conventional fuel vehicles exhibit negative compliance performance following the implementation of CAFE II. The overall sales-weighted CAFE compliance results suggest that, despite the more stringent standards of Phase II, the increased sales of BEVs, coupled with the application of incentive multipliers, led to higher compliance performance in 2022–2023 compared to CAFE I.

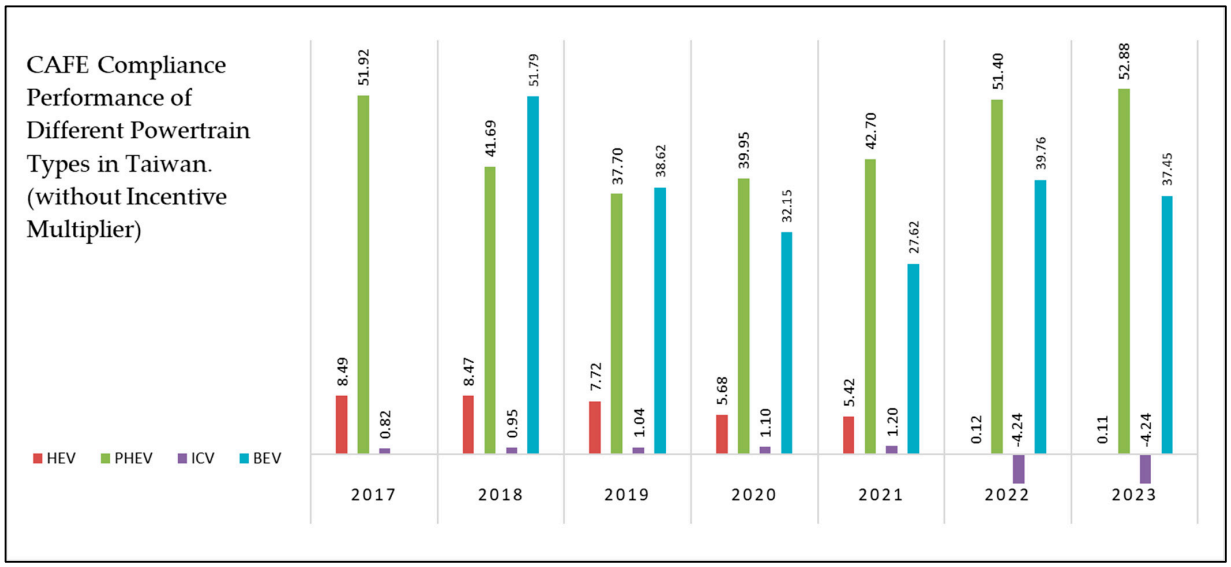

Figure 5. Compliance performance of powertrain types to the CAFE framework adopted in Taiwan without the application of incentive multipliers.

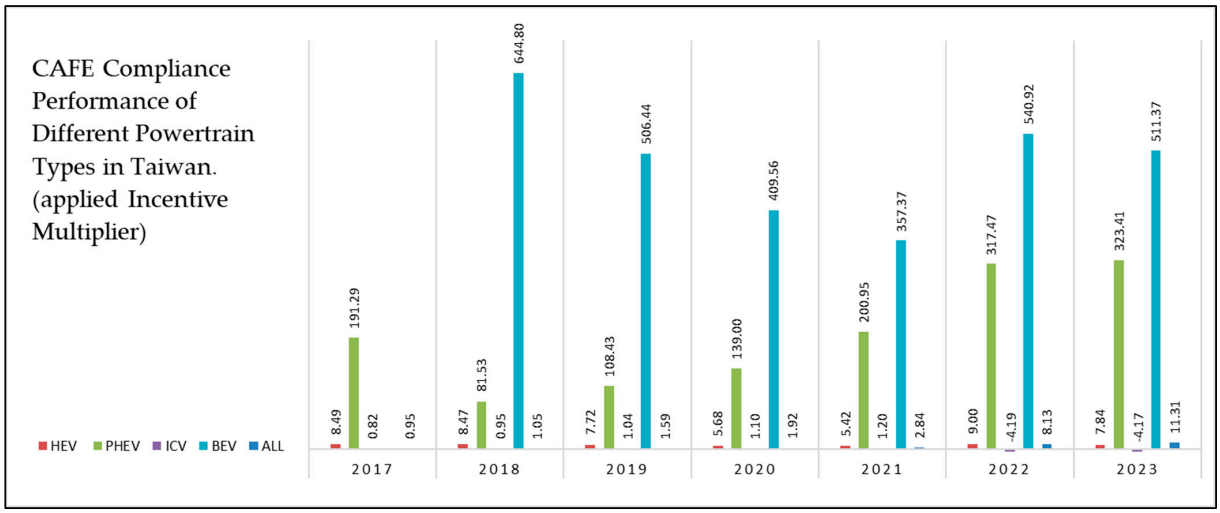

Figure 6. Compliance performance of powertrain types to the CAFE framework adopted in Taiwan with the application of incentive multipliers.

Taiwan's CAFE system includes a credit accumulation mechanism aligned with international practices. If a manufacturer's annual CAFE performance exceeds the regulatory compliance requirements, the manufacturer receives excess credits that can be carried forward for up to four years. Figure 7 illustrates the cumulative credit balance in the Taiwan CAFE system over the years. The inclusion of pure electric vehicle manufacturers within the regulatory framework under the second phase of CAFE has significantly increased the positive credits in the overall credit pool. However, as this is only the second year of CAFE Phase II, it may be too early to assess the long-term impact of these additional credits on the overall average fuel efficiency growth.

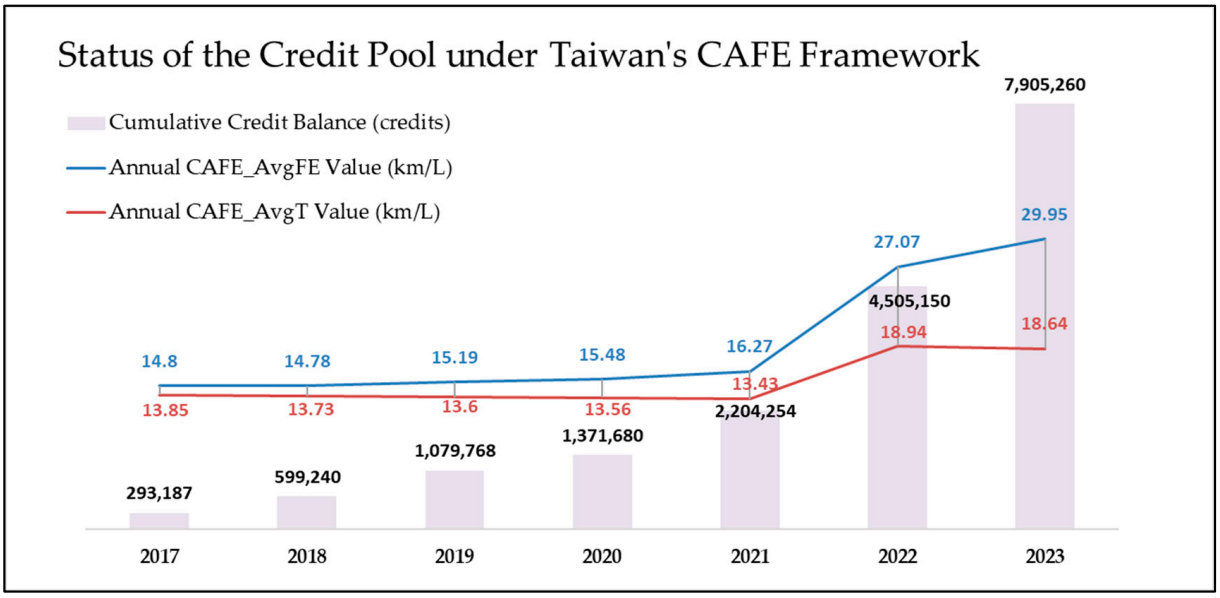

Figure 7. Status of the credit pool under the CAFE framework adopted in Taiwan.

5. Discussion

5.1. Taiwan Has Shaped a Localized CAFE System Based on Its Unique Industrial Environment and Small-Scale Market

The Corporate Average Fuel Economy (CAFE) standards, originally designed by the United States for a large vehicle market, serve as a vehicle efficiency management tool. However, when applied to smaller new vehicle markets, these standards may present challenges and are associated with different outcomes.

From a market perspective, a smaller domestic market may limit the operational scale of manufacturers, potentially impacting the cost-effectiveness of implementing CAFE standards. The economies of scale that manufacturers benefit from in larger markets may not be achievable in smaller markets such as Taiwan. Additionally, the effectiveness of CAFE standards is closely tied to consumer preferences, which can vary significantly in smaller markets. These differing preferences may slow down the transition to compliant vehicle models, making the process more challenging.

From a technical perspective, CAFE standards require significant improvements in vehicle energy efficiency. In Taiwan, the annual volume of new vehicles produced domestically and imported is roughly equal, with a 50/50 split. Most domestic manufacturers focus on optimizing their vehicle portfolio to meet minimum compliance requirements in a cost-effective manner. However, these manufacturers rely primarily on technical licensing from the parent brands, and few engage in independent research, design, and production. Consequently, investment in advanced vehicle R&D is prohibitively expensive for domestic manufacturers, who are also constrained by their parent brands' willingness to provide ongoing technical support.

In contrast, importers have greater flexibility in their vehicle offerings and can meet regulatory requirements by sourcing electric or high-efficiency models from their foreign parent companies. While the cost of importing these models is currently higher than that of conventional fuel vehicles, it remains more economically feasible than investing in R&D and local production.

Regardless of whether they are domestic or import manufacturers, if they are unable to achieve higher compliance performance through the aforementioned methods or cannot meet compliance deadlines, they may seek credit transfers from other manufacturers. However, the credit market in a small-scale environment such as Taiwan presents its own challenges, with the cost and availability of credit transfers being less predictable due to the composition of market participants.

5.2. Potential Credit Market Issues for Small-Scale CAFE Regulated Entities Under a Relatively Favorable CAFE Framework

The credit mechanism plays a crucial role in the CAFE system, as numerous studies have highlighted its ability to enhance compliance flexibility for manufacturers, encourage technological investment, and support long-term planning [40]. However, the credit mechanism may also have certain adverse effects. For instance, if manufacturers accumulate sufficient credits, they may lack the incentive to improve vehicle efficiency in specific target years, resulting in the actual impact of tighter standards being less significant than expected. This could potentially slow national progress in energy efficiency and affect the fairness of market competition [41–43].

Reflecting on Taiwan's CAFE framework at the end of 2023, it is evident that the system was relatively favorable to regulated manufacturers. The first-phase standards were lenient, allowing for a four-year credit carryover. As manufacturers entered the second phase, they could rely on credits from the first phase, which reduced the urgency to improve efficiency. Additionally, the introduction of high incentive multipliers for electric vehicles further increased credit accumulation (Figure 7), leading to minimal pressure on manufacturers.

The surplus of credits leads to limited credit trading activity among manufacturers within the market. In addition, the small-scale nature of Taiwan's CAFE-regulated market

makes it challenging to establish reasonable compliance costs through market mechanisms for credit trading. In Taiwan, the price of credit trading is not regulated by the government but is determined by market mechanisms. Consequently, the actions of a single buyer or seller in a small market can significantly impact pricing, making it difficult for prices to naturally adjust to external economic conditions.

In practice, the credit trading market in Taiwan has very few participating manufacturers, resulting in limited competition and even fewer buyers with actual demand. The small scale of new vehicle sales means that the required credits represent only a minor portion of the total market surplus. As a result, buyers can easily acquire the necessary credits at low cost, reducing the incentive to invest in improving vehicle energy efficiency. Compared to larger international markets, a small-scale market like Taiwan's may require more government or regulatory intervention to stabilize it.

5.3. The Discussable Fuel Conversion Factor for Electric Vehicles from a Future Net-Zero Perspective

A key factor to consider in Taiwan's future CAFE framework is the fuel conversion factor for electric vehicles. Japan has announced that by 2030, the method for converting fuel efficiency equivalents should incorporate the well-to-wheel (WTW) concept, which considers the entire life-cycle of fuel use. This approach is essential to better align with long-term net-zero carbon emission goals [44].

Different countries that use energy efficiency as a management indicator, such as the United States, Japan, and China, use slightly different energy conversion factors in their vehicle energy efficiency regulations. For example, Japan converts 1 L of automotive gasoline to 9.14 kWh (9140 Wh/L) [44], while the U.S. EPA suggests 8887 gCO_2 per gallon for gasoline [45]. In China, the conversion factor is approximately 8620 Wh/L [29].

Therefore, even when using the same vehicle efficiency testing methods, converting the efficiency of electric vehicles to a common baseline for comparison with fuel vehicle efficiency can result in differences in compliance outcomes across countries due to varying energy conversion rates. However, the impact of these conversion differences is relatively minor compared to the variations that would occur if the full life-cycle of the fuel or energy were considered.

The European Union uses vehicle CO_2 emissions as a management indicator, with electric vehicles considered to be zero-emission in operation, allowing for direct comparison without energy value conversion. As a result, electric vehicles may show greater compliance benefits than those calculated using energy conversion methods. However, recent studies suggest that measuring energy consumption or CO_2 emissions per unit of distance driven does not fully capture the economic or environmental benefits of vehicle energy. To accurately assess and compare the energy efficiency or CO_2 emissions of different vehicles, it is necessary to consider the efficiency losses and carbon emissions throughout the entire energy production and consumption process.

Table 4 compares how major countries and territories calculate and evaluate vehicle energy consumption and CO_2 emissions within their regulatory frameworks. To date, only Japan has explicitly incorporated the WTW (well-to-wheel) concept into its 2030 standards, announced in 2020 [44]. Additionally, both the European Union and China have indicated possible future adoption of WTW or LCA (life-cycle assessment) methods as evaluation boundaries [28,29].

Table 4. Comparison of vehicle emission regulatory evaluation boundaries in different countries [19,28,29,44–48].

Market	Regulatory Evaluation Boundary	Description
Japan	Well to Wheel	In 2020, Japan established fuel efficiency standards for passenger cars, including EVs and PHEVs, to be met by 2030. These standards incorporate a WTW fuel efficiency conversion formula into the regulatory framework, taking into account the projected electricity supply in 2030.
European Union	Tank to Wheel (Voluntary LCA data submission expected from 2026)	Regulation (EU) 2019/631 set CO_2 emission targets for passenger cars by 2030, emphasizing the importance of life-cycle assessment (LCA). Regulation (EU) 2023/851 requires the European Commission to propose LCA methodologies and data reporting guidelines by the end of 2025. From 1 June 2026, manufacturers can voluntarily submit life-cycle CO_2 emissions data for new passenger cars and light-duty trucks.
China	Tank-to-wheel (LCA-based standards are being considered post-2025)	Established 2025 fuel efficiency standards for passenger cars, calculated using the tank-to-wheel (TTW) approach. For electric vehicles (EVs) and fuel cell vehicles (FCVs), energy consumption and carbon emissions are assumed to be zero by 2025. According to China's national standard (GB/T 37340-2019), three formulas and related coefficients have been introduced: (1) Simple heat value conversion (TTW) (gasoline 0.1161 L/1 kWh) (2) Fuel life-cycle heat value conversion (WTW) (gasoline 0.224 L/1 kWh) (3) Fuel life-cycle CO_2 emission (WTW) (gasoline 0.264 L/1 kWh)
United States	Tank to Wheel	Current CAFE and GHG standards use TTW; LCA and WTW assessments are used primarily as references for policy formulation.
South Korea	Tank to Wheel	Current standards use TTW; most WTW research in South Korea focuses on energy structure and hydrogen vehicle development policy.
Taiwan	Tank to Wheel	Current standards use TTW; a localized GEERT model is being developed for policy reference.

Already in 2019, the EU mentioned in Regulation (EU) 2019/631 that it would assess life-cycle CO_2 emissions of vehicles [28]. However, no specific methodology was announced at that time. Later, in Regulation (EU) 2023/851, the EU stated that it would develop a LCA assessment methodology and data reporting system by the end of 2025. From 1 June 2026, manufacturers will be allowed to voluntarily submit life-cycle CO_2 emissions data for newly sold passenger cars and light commercial vehicles [46].

Similarly, China introduced the "Energy Consumption Calculation Method for Electric Vehicles" (GB/T 37340-2019) [47] in 2019, which provides three formulas for converting electric vehicle efficiency into fuel efficiency equivalents based on tank-to-wheel (TTW), WTW, and WTW CO_2 assessments. Although China's regulatory assessment boundary will primarily use TTW until 2025, the possibility of shifting to WTW has not been ruled out, and relevant assessment methodologies are already in place.

Currently, the United States, South Korea, and Taiwan primarily use the TTW approach, with LCA and WTW research projects serving primarily as references for policy development.

In the context of the global trend toward net-zero carbon emissions, if Taiwan seeks to align its vehicle energy efficiency management with international standards, it cannot overlook the increasing focus on the life-cycle of automotive energy or the vehicle life-cycle itself. As Taiwan advances to the next phase of CAFE, incorporating LCA into the CAFE system would necessitate a comprehensive review and redesign of the entire CAFE framework. This would lead to the development of a more extensive and intricate vehicle energy management system.

6. Conclusions

Taiwan, highly dependent on imported energy, has long prioritized energy conservation. Since the introduction of vehicle energy efficiency management in 1988, the adoption of the CAFE system has significantly improved vehicle energy efficiency over the past decade. Despite the gradual rise in new vehicle sales in recent years, overall energy consumption in road transportation has remained stable.

This study provides a comprehensive analysis of Taiwan's CAFE system design, examines the compliance performance of various powertrain types under its framework, and assesses whether the CAFE system effectively supports Taiwan's evolving vehicle energy efficiency policy goals. It also compares the energy efficiency evaluation methods used in Taiwan's CAFE framework with international practices. Looking toward a net-zero carbon future, if life-cycle assessment (LCA) becomes a key trend, Taiwan's CAFE system will require a thorough review and redesign, potentially resulting in a more complex regulatory framework.

The CAFE system has proven effective in improving vehicle energy efficiency in smaller markets such as Taiwan, but it faces certain limitations and challenges. The small market size may affect the cost-effectiveness of CAFE implementation. From a technical perspective, a smaller new vehicle market may not provide adequate support for the automotive industry. For example, domestic manufacturers in Taiwan largely rely on technical support from parent companies, and local R&D capabilities are relatively limited. As a result, the cost of complying with stricter CAFE standards is higher, and the ability to meet policy targets remains uncertain. Additionally, the credit market for small-scale CAFE-regulated entities, such as those in Taiwan, presents unique challenges. The cost and availability of credit transfers are difficult to predict due to the composition of market participants.

Moreover, Taiwan's upcoming third phase of CAFE standards faces a significant challenge: the surplus credits generated by the favorable design of the first and second phases may reduce manufacturers' incentives to comply. This calls for a review of the design of the current system. Incentive multipliers, which are considerably higher than those in other countries, should be reconsidered. It is also essential to manage the excess credits in the market. A gradual tightening of CAFE standards could help absorb these excess credits and ensure continued progress toward compliance. Furthermore, if the net-zero emissions policy is established as a long-term objective, life-cycle energy efficiency assessments should be incorporated into the new CAFE mechanism.

In smaller markets, where both the new vehicle market and the number of automakers are limited, even small changes in key variables—such as the number of electric vehicles—can have a significant impact on CAFE calculations. This effect is further amplified by preferential measures, resulting in greater fluctuations compared to larger markets. Therefore, adopting incentive structures based on benchmarks from larger markets may not yield positive outcomes. It is crucial to take into account the specific market size and industrial capacity to ensure that the CAFE mechanism remains effective in driving vehicle energy efficiency improvements without undermining broader policy goals.

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