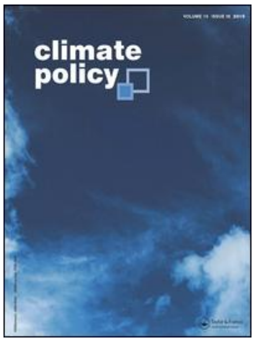

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RESEARCH ARTICLE

A blockchain-based emissions trading system for the road transport sector: policy design and evaluation

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ABSTRACT

Emissions trading is a cost-effective climate policy for reducing greenhouse gas emissions. It could also be useful for addressing road transport emissions, especially given that this sector is the largest CO_2 emitter in the transportation sector and its emissions continue to increase. However, emissions trading for road transport (ETS-RT) has rarely been implemented due to its complexity. This paper designs a novel and practical policy framework for an ETS-RT based on advanced blockchain technology, including all related entities upstream, midstream and downstream of the road transport sector. First, the government determines the cap and allocates the initial permits. Then, fuel producers, vehicle manufacturers, and vehicle users are involved as regulated entities with tradable emission permits. They are responsible for the three determinants of CO_2 emissions in the road transport sector: fuel emission factors, vehicle fuel economy, and vehicle miles travelled, respectively. With all the regulated entities collaborating on compliance, the three determinants can be synergistically optimized so that the efficiency of the emissions abatement can be maximized. In addition, all trading, monitoring, reporting, and verification of the emission permits are automatically executed and recorded via a smart contract deployed on a decentralized blockchain. This approach can dramatically reduce administrative costs, improve transparency and traceability, and eliminate double counting and fraud. Finally, the proposed policy was evaluated using a multicriteria analysis method compared with other possible ETS-RT approaches.

Key policy insights:

- Fuel producers, vehicle manufacturers, and vehicle users – who are respectively responsible for fuel emission factors, vehicle fuel economy and vehicle miles travelled – should be synergistically regulated in an ETS-RT to maximize the efficiency of emissions abatement.
- This can be enabled by advanced blockchain technology, which can eliminate the need for a central authority, while enhancing transparency, traceability and cost-effectiveness.
- Blockchain technology could also be useful for monitoring, reporting and verification under the Paris Agreement.
- A blockchain-based ETS-RT is found to outperform other forms of ETS on criteria of acceptability, feasibility and environmental performance.

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1. Introduction

The transport sector produced 8 billion tons of carbon dioxide (CO_2) emissions globally in 2017, accounting for 24% of CO_2 emissions from energy use (IEA, 2019). This sector is the second-largest emitter, next to the electricity and heat generation sector, and its emissions have continued to increase rapidly since 1990. In addition, 68% of the increase was led by rising emissions from the road transport sector, which accounted for three-quarters of the transport emissions in 2017. Therefore, mitigation and reduction of CO_2 emissions are urgently needed in the road transport sector.

According to the decomposition of CO_2 emissions[1] in the road transport sector, there are three determinants: fuel emission factors, vehicle fuel economy, and vehicle miles travelled (VMT), which are attributed to fuel producers, vehicle manufacturers, and vehicle users, respectively (Creutzig et al., 2011). Therefore, most current policy instruments target these regulated entities by focusing on the respective determinants (as shown in Figure 1). However, these non-market policy instruments cannot guarantee an absolute emission reduction target for the road transport sector because of the uncertainty and rebound effect. For example, the Corporate Average Fuel Economy (CAFE) standards make vehicles more efficient, so people may tend to use vehicles more frequently due to the decreased fuel cost. Therefore, total emissions will not necessarily decrease with one determinant increasing and another decreasing.

However, a market-based mechanism, which puts a price on greenhouse gas (GHG) emissions, such as a carbon tax or emissions trading system (ETS), could address the above problems via the price signal. According to Flachsland et al. (2011), 'a well-designed market-based instrument can provide abatement incentives across all available emission reduction options (within and across sectors) at harmonized marginal costs of abatement'. In an ETS, for example, an emissions cap is determined for the sectors included in the trading system (Winkelman et al., 2000). Thus, the uncertainty and the rebound effect can be eliminated. The emission cap is then allocated to regulated entities, who must hold permits for their emissions. To achieve compliance, they may either reduce emissions themselves or purchase permits from other entities. This policy provides flexibility for the regulated entities and minimizes their abatement costs. In addition, the trading of permits provides more benefits for those entities who reduce emissions and can thereby encourage the innovation of, and investment in, low-carbon technology.

However, ETS for road transport (hereafter referred to as ETS-RT) has been rarely implemented or studied, since including the millions of mobile sources and multiple stakeholders in the transport sector into an existing ETS is challenging. To fill the gap, this study aims to design a novel and practical policy framework for ETS-RT based on advanced blockchain technology, which incorporates all related entities in the road transport sector, including fuel producers, vehicle manufacturers, and vehicle users. As a result, all three determinants of CO_2 emissions in the road transport sector can be synergistically optimized through the market mechanism.

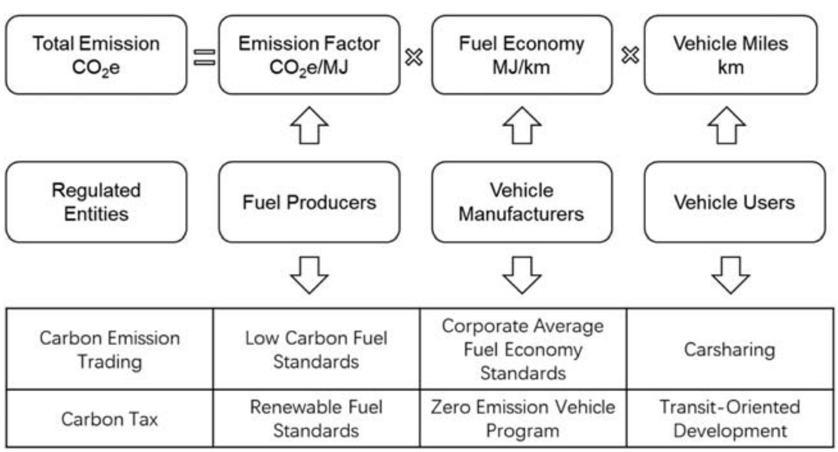

Figure 1. Decomposition of CO_2 emissions in the road transport sector.

Additionally, emission permit trading between regulated entities is enabled by blockchain technology, which eliminates the need for a central authority. This can dramatically reduce administrative costs and improve the system's transparency and traceability. Therefore, this study contributes to designing a more effective and advanced ETS-RT which may be used to guide policy implementation.

The remainder of this paper is organized as follows: Section 2 reviews the literature related to ETS, ETS-RT, and blockchain technology. A policy framework for blockchain-based ETS for road transport (hereafter referred to as BC-ETS-RT) is presented in Section 3. Multicriteria analysis is adopted to evaluate the BC-ETS-RT, and its potential effects, as well as concerns, are discussed in Section 4. The final section presents the conclusions and limitations of this study and suggests some future research directions.

2. Literature review

2.1. ETS for the road transport sector

Only a few jurisdictions have incorporated the road transport sector into their ETS (e.g. California and Quebec required transport fuel suppliers to be included in their provincial Cap-and-Trade Systems). However, many researchers have attempted to explore how to design and implement an ETS-RT (Li & Tang, 2017). Depending on the regulated entity that holds the emission permit, an ETS-RT can be abstractly divided into three approaches: upstream, midstream, and downstream, corresponding to fuel producers, vehicle manufacturers, and vehicle users, respectively (Iankov & Zito, 2008; Millard-Ball, 2008; Mock et al., 2014). For comparison, the characteristics of these three types of approaches are summarized in Table 1.

In an upstream ETS-RT, emission permits are allocated to fuel producers annually (Jochem, 2009). Theoretically, this approach can cover the largest range of emission sources because the number of fuel producers is much smaller than the number of vehicles (Sorrell, 2010). For example, Grayling et al. (2006) proposed incorporating the road transport sector into the EU ETS by regulating fuel producers, which can reduce the management difficulty and cost. Thus, this approach is considered the most feasible method, with the advantages of low cost, easy design, and high political acceptance. However, the options for fuel producers to reduce emissions are limited. Apart from reducing emissions in the production process, the only way is to change the carbon intensity of fuels, which also drives an increase in the fuel price (Millard-Ball, 2008). In practical applications, emission reductions achieved would be very limited because of inelastic demand for travel and motorist insensitivity to slight increases in the fuel price (Graham & Glaister, 2002; Millard-Ball, 2008).

Downstream ETS-RT originated from tradable fuel permits that are allocated to vehicle users for travel activities (Dobes, 1998). Different schemes for such a downstream ETS-RT have been proposed for the UK and elsewhere (Fawcett & Parag, 2010). Parag and Eyre (2010) use a general term, personal carbon trading (PCT), to describe a variety of downstream cap-and-trade policies. Many studies indicate that PCT for road transport would be an efficient way to reduce transport emissions because it drives people to reduce VMT and to choose more efficient vehicles (Li et al., 2017b). In addition, Wadud et al. (2008) show that consumers are more sensitive to the price signal of the permit in a downstream ETS-RT, which thus exerts a greater influence on the vehicle type chosen, VMT, and residential location (Aziz et al., 2015). However, many researchers have argued that the downstream approach is unrealistic because of the high transaction and administrative costs for thousands of entities (Millard-Ball, 2008). Nonetheless, Raux et al. (2015) believe that high costs can be reduced by innovations in technology. For instance, storing carbon permits in a smart card is one possible

Table 1. Comparison of the Different ETS Approaches for Road Transport.

Approach	Regulated Entity	Influencing Objects	Advantages	Disadvantages
Upstream	Fuel Producers	Fuel emission factor	Low management costs; wide coverage	Weak reduction effects
Midstream	Vehicle Manufacturers	Vehicle fuel economy; the proportion of new energy vehicles	Lower management costs; promotes innovations	Incomplete coverage
Downstream	Vehicle Users	Vehicle miles travelled; choice of vehicle; residential locations	Strong incentive; significant reduction effects	High cost; difficult to implement

way to reduce costs (Starkey & Anderson, 2005). Where these are widespread, mobile phones may also provide a simple and cost-effective way to transact the permits (Al-Guthmy & Yan, 2020).

Midstream ETS is a tradeoff solution in which vehicle manufacturers are the regulated entities (Winkelman et al., 2000). This scheme could encourage vehicle manufacturers to improve fuel economy and reduce emissions. Michaelis and Zerle (2006) propose that the initial permit should be allocated according to baseline and historical sales. In addition, this baseline would decline year by year, which would force vehicle manufacturers to develop low-emission vehicles unless they purchase permits from other manufacturers. Therefore, the advantages of this approach include avoiding an increase in the price of fuels, reducing administrative costs, and stimulating consumers to choose more efficient vehicles (German, 2007; Michaelis & Zerle, 2006). However, the midstream approach also has some issues. First, determining the emission cap is difficult, since vehicle manufacturers cannot influence the actual emissions of the vehicles after they are sold. Second, this approach cannot cover the emissions of all vehicles if only the new entrant vehicles are regulated.

Overall, most of these approaches involve a single type of regulated entity, and thus only one of the three determinants can be influenced. For example, the upstream approach, which regulates the fuel producers, can only change the emission factors of the fuels used in the road transport sector. However, this approach results in little incentive to improve the fuel economy of the vehicles or the VMT by vehicle users. Therefore, the efficiency of emission abatement is limited. To the authors' knowledge, this paper represents the first attempt to integrate upstream, midstream, and downstream approaches for an ETS-RT to maximize the effectiveness and efficiency of the policy.

2.2. Blockchain technology and its application

Blockchain was invented by Satoshi Nakamoto in 2008 to serve as the public transaction ledger of the cryptocurrency Bitcoin, which is a peer-to-peer electronic cash system without the need for a trusted authority or central server (Nakamoto, 2008). In short, blockchain is a decentralized, distributed, and public digital ledger for recording transactions across all consensus nodes. This system provides two favourable characteristics that make it attractive as a transaction recording solution: (1) cryptographic immutability and verifiability, making it impossible to modify transaction records once committed, thus ensuring secure transactions; and (2) distributed consensus, allowing anonymous individuals across a peer-to-peer network to come to an agreement on the state of the network, thus removing the need for a centralized agreement mediator organization (Nakamoto, 2008). As a result, this system can change the nature of executing transactions and redefine existing business modes.

Emerging from the application of Bitcoin, blockchain technology can be further integrated into multiple areas (e.g. financial services, the food industry, and the energy market) (Chitchyan & Murkin, 2018) combined with smart contracts (Christidis & Devetsikiotis, 2016). Blockchain-based smart contracts are computer programmes stored on the blockchain that could be partially or fully executed or enforced without human interaction (Franco, 2014). These programmes can express the contents of a contractual agreement and automatically implement the content on the basis of triggers provided by the users or extracted from the environment. Smart contracts are currently promoted as the means to leverage efficiency, security, and impartiality in the execution of an agreement, thereby reducing the costs in implementing contracts and increasing trust between parties (Idelberger et al., 2016). Therefore, these contracts allow for more complex transactions than simply exchanging digital tokens on the blockchain.

Blockchain can also contribute to ETS by building trust and avoiding fraud (Chapron, 2017). At present, most existing ETS are run on centralized systems with high transaction costs, instances of fraud, and double counting issues that undermine their effectiveness. Combining the ETS with blockchain technology can eliminate the need for a central authority to oversee the trading of emission permits. It can also improve the transparency, traceability, and cost-effectiveness of the ETS by enabling peer-to-peer trading of permits on a mutually distributed network.

However, only a few researchers have proposed preliminary ideas on the application of blockchain in ETS. For example, Khaqqi et al. (2018) proposed a novel ETS model supported by blockchain technology and a reputation-based trading mechanism to improve ETS efficacy. Fu et al. (2018) presented a blockchain-enhanced ETS framework in the fashion apparel manufacturing industry, which demonstrates how carbon emissions could be easily measured and recorded with less human labour. Al Kawasmi et al. (2015) designed a Bitcoin-based decentralized ETS and found that, by providing systematic decentralization, privacy, and security protection for the carbon emission traders, their participation and the overall trading activity would increase.

The above literature provides a foundation for this study, yet there is no published research on the application of blockchain to an ETS-RT. Since ETS-RT involves the monitoring and management of a large number of mobile emission sources, its implementation is more complex. Fortunately, advanced blockchain technology makes it possible to easily track the activities and emissions of upstream, midstream, and downstream entities in the road transport sector. This paper represents the first application of blockchain technology to ETS-RT to reduce administrative costs and overcome implementation challenges.

3. Policy framework design

This section presents the concepts and policy framework design of the proposed BC-ETS-RT, which integrates the upstream, midstream, and downstream approaches. Figure 2 provides a schematic depiction of the system, where the government plays the roles of regulator and supervisor of the system, while fuel producers, vehicle manufacturers, and vehicle users are involved as regulated entities with tradable emission permits. The fuel emission factors, vehicle fuel economy, and the VMT are the regulated objects corresponding to the regulated entities. Details on the approach to design the BC-ETS-RT are presented below.

3.1. Coverage and obligation demarcation

The road transport sector is responsible for the majority of GHG emissions in the transportation sector, with CO_2 emissions accounting for 96.6% of the total (Davis et al., 2018). Thus, the coverage of the ETS-RT is the on-road CO_2 emissions emitted by all vehicles in the road transport sector. It should be noted that the ETS-RT only focuses on the 'tank-to-wheels' emissions. The 'well-to-tank' and other indirect emissions can be covered by other sectors (e.g. electricity, heat, and industry sectors) in the ETS.

As the direct emitters of CO_2, vehicle users, including both the individual owners and transportation companies (e.g. public transport, taxis, ridesourcing, carsharing, freight companies), are liable for emissions reduction and should thus keep their transport emissions below the limits of the permits they hold (Li et al., 2017a). The fuel producers (including but not limited to fuel retailers, fuel suppliers, and oil refineries) are liable to reduce the fuel carbon intensity, since most CO_2 emissions come from burning the fuels they

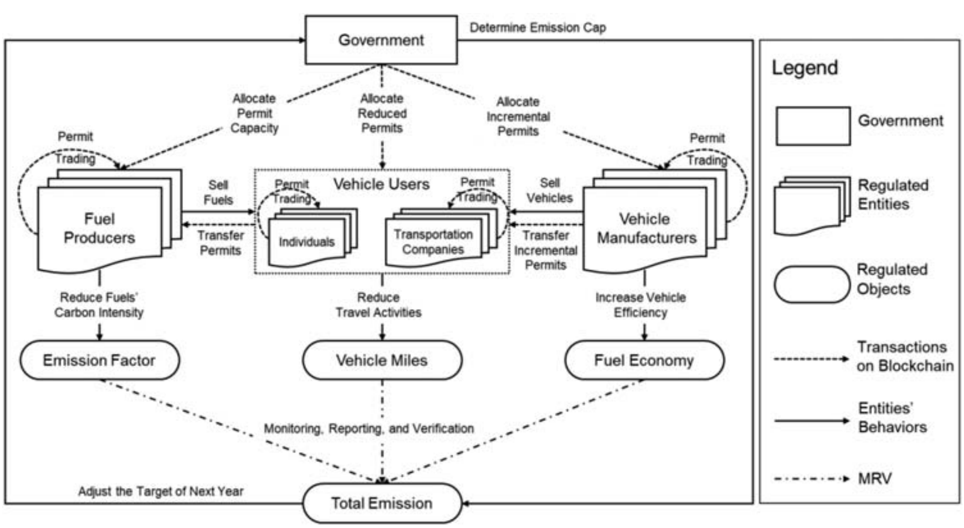

Figure 2. Schematic diagram of the BC-ETS-RT.

produce and sell. In addition, vehicle manufacturers are obligated to increase the fuel economy of the vehicles they sell because these vehicles are emission sources. Therefore, the regulated entities consist of all vehicle users, fuel producers, and vehicle manufacturers, who are also emission permit holders.

3.2. Emission cap determination

The total emissions that cannot be exceeded for the road transport sector in the target year is set as the cap on emission permits. This cap is mainly determined by the total emissions in the base year and the emission reduction potential of each subsector (e.g. private cars, taxis, buses, light trucks, medium trucks, and heavy trucks). On the one hand, a reduced cap on emissions of existing vehicles should be set to encourage decreased VMT, the scrapping of old high-emission vehicles, and cleaner fuels. On the other hand, an incremental cap on emissions of new entrant vehicles should also be set to allow for economic growth and demand for new vehicles. Therefore, the cap on emission permits consists of two parts: one is a reduced cap and the other is an incremental cap.

First, the reduced cap in a target year can be calculated using the top-down method (Li et al., 2019a) based on the fuel consumption data in the base year. The cap can be formulated by the sum of the products of total fuel consumption and the emission factors of each type of existing vehicle and fuel, as follows:

$$Ce^t = \sum_i \sum_k (TFe_{ik}^{t-1} \times E_k^{t-1}) \times (1 - Re_i^t) \tag{1}$$

where Ce^t is the reduced cap on the emissions of existing vehicles in the target year (t), TFe_{ik}^{t-1} is the total fuel consumption of existing vehicle type (i) using fuel type (k) in the base year (t-1), E_k^{t-1} is the emission factor of fuel type (k) in the base year (t-1), and Re_i^t is the emission reduction rate for the existing vehicle type (i), which may reflect the potential to decrease vehicle mileage, scrap old high-emission vehicles, and reduce the fuel emission factors for existing vehicles.

Second, the incremental cap is determined by the projected number and average annual emissions of each type of new entrant vehicle in the target year. Similar to the quantity control of vehicle registration plates and emission standards, these two factors could be pre-decided by policymakers based on historical data and the emission reduction target. The incremental cap can then be calculated as follows:

$$Cn^t = \sum_i Nn_i^t \times \overline{AEn}_i^t \tag{2}$$

$$\overline{AEn}_i^t = \frac{\sum_k TFe_{ik}^{t-1} \times E_k^{t-1}}{Ne_i^{t-1}} \times (1 - Rn_i^t) \tag{3}$$

where Cn^t is the incremental cap on the emissions of new entrant vehicles, Nn_i^t is the projected number of new entrant vehicles of type (i), $\overline{AEn}_i^t$ is the benchmark emission of new entrant vehicles of type (i), and Rn_i^t is the emission reduction rate for the new entrant type (i) vehicles, which may reflect requirements to decrease the vehicle mileage, improve fuel economy, and reduce the fuel emission factor for new entrant vehicles. Since the emission reduction potential of new entrant vehicles may be greater than that of existing vehicles, the reduction rate of new entrant vehicles should be stricter than that of existing vehicles, i.e. the value of Rn_i^t is usually larger than the value of Re_i^t.

The total cap on emissions in the target year (C^t) is then the sum of the reduced cap for existing vehicles and the incremental cap for new entrant vehicles:

$$C^t = Ce^t + Cn^t \tag{4}$$

3.3. Initial permit allocation

Compared with allocation methods where permits must be purchased, such as auctioning or fixed-price sales, the free allocation of permits is more easily accepted by regulated emitters. Although problems of equity and efficiency exist, implementation is simple and practicable, especially during pilot periods (Jiang et al., 2016). In the EU ETS, for example, 85% of total aviation allowances were freely issued to airlines during the first phase of the aviation ETS. Therefore, in the first stage of the BC-ETS-RT policy, free allocation of initial emission permits is adopted to increase the acceptability of the policy for regulated entities. However, auctioning would be introduced to ensure efficiency and social equity in the future when the market is mature.

There are two common approaches in the context of free allocation of initial permits: grandfathering and benchmarking. With the grandfathering approach, covered entities receive emission permits according to their historical emissions in a base year or base period. This approach has been criticized as rewarding higher emitters and requiring further provisions for new entrants. The benchmarking approach allocates permits based on performance indicators which can better encourage emission reduction behaviours and more easily assimilate new entrants. Since benchmarking is preferable to grandfathering in terms of efficiency, equity, and political acceptance, the benchmarking approach was chosen to determine the free allocation of initial permits for vehicle users, vehicle manufacturers, and fuel producers.

3.3.1. Allocation for vehicle users

The reduced cap for existing vehicles is directly allocated to vehicle users in the road transport sector. Whenever the users purchase fuel, they have to transfer the quantity of fuel emissions from their permitted allowance to the fuel producer. If a vehicle user runs out of emissions on his/her permit, then s/he cannot travel anymore unless a permit is purchased from another user.

For administrative convenience, the initial permits are only allocated to the owners of the vehicles. Users who do not own vehicles themselves (e.g. if they use a vehicle by carsharing, ridesourcing, or public transport) need to buy the corresponding emission permit from the vehicle owner, in addition to any transportation service pricing (Li et al., 2019b).

Given that different types of vehicles (e.g. private cars, commercial cars, taxis, buses, light trucks, medium trucks, and heavy trucks) may have different usages and mileages, a benchmark method is proposed to calculate the permits for different types of vehicles. This benchmark can be determined by the average annual emissions and targeted reduction rate of each type of existing vehicle. The initial permits of vehicle users can then be calculated as follows:

$$\overline{AEe_i^t} = \frac{\sum_k TFe_{ik}^{t-1} \times E_k^{t-1}}{Ne_i^{t-1}} \times (1 - Re_i^t) \tag{5}$$

$$Pe^t(u) = \sum_i Nec_i^{t-1}(u) \times \overline{AEe_i^t} \tag{6}$$

where $\overline{AEe_i^t}$ is the benchmark emission of an existing vehicles of type (i), $Pe_i^t(u)$ is the initial permit of vehicle user (u) in the target year (t), and $Nec_i^{t-1}(u)$ is the number of vehicles of type (i) that the user (u) owns in the base year (t-1).

3.3.2. Allocation for vehicle manufacturers

The incremental cap for new entrant vehicles is first allocated to the vehicle manufacturers before the vehicles are sold to consumers. When a consumer buys a new car from the manufacturer, the initial permit of this car will be transferred from the account of the manufacturer to the account of the vehicle user. If manufacturers run out of permits, they cannot sell new vehicles in the target year unless they buy the requisite permits from other manufacturers.

Constrained by the incremental cap on the emissions of new entrant vehicles, the initial permit of the vehicle manufacturer (m) is determined by the projected number and benchmark emissions of new vehicles, as follows:

$$Pn^t(m) = \sum_i Nn_i^t(m) \times \overline{AEn_i^t} \tag{7}$$

where $Pn^t(m)$ is the initial permit of the vehicle manufacturer (m), $Nn_i^t(m)$ is the projected number of new entrant type (i) vehicles that manufacturer (m) sold in the target year (t), and $\overline{AEe_i^t}$ is the benchmark emission of new entrant vehicles of type (i).

3.3.3. Allocation for fuel producers

The fuel producers are the collectors of the permits, since all vehicle users should transfer permits to them when refuelling. To keep the total fuel emissions below the cap, a permit capacity should be allocated to each fuel producer. In other words, the number of permits that the fuel producers collect cannot exceed the permit capacity they have.

To encourage fuel producers to reduce the fuel emission factors and develop low carbon fuels, the initial permit capacity is determined by the projected sales and benchmark emission factors of fuels, which can be calculated as follows:

$$\bar{E}_k^t = \frac{\sum_k TF_k^{t-1} \times E_k^{t-1}}{\sum_k TF_k^{t-1}} \times (1 - R_k^t) \tag{8}$$

$$PC^t(p) = \sum_k TF_k^t(p) \times \bar{E}_k^t \tag{9}$$

where $\bar{E}_k^t$ is the benchmark emission factor of fuels of type (k), R_k^t is the reduction rate of the emission factor for the fuel type (k), $PC^t(p)$ is the initial permit capacity of fuel producer (p) in the target year (t), and $TF_k^t(p)$ is the projected sales of fuel type (k) of fuel producer (p) in the target year (t).

3.4. Blockchain-based permit transactions

Permit transactions between the regulated entities are implemented via a smart contract deployed on the blockchain which can self-execute if certain conditions are met, while avoiding the services of intermediaries. All the transactions will finally be verified and confirmed via a distributed consensus mechanism, such as Proof of Work, Proof of Stake, Delegated Proof of Stake, and Practical Byzantine Fault Tolerance (Sankar et al., 2017). As a result, transaction costs are dramatically reduced. In addition, transaction records on the blockchain cannot be altered or repudiated because of its decentralization and encryption.

Every entity in this system has an account with a unique address to store the permit and token (a virtual currency that changes into money at a constant exchange rate of 1:1). The smart contract also has an account to execute the transaction independently and automatically in a prescribed manner (Christidis & Devetsikiotis, 2016). There are three types of transactions that are possible among the three types of regulated entities, as discussed further below.

3.4.1. Permit trading between the same types of entities

To ensure that emission reductions are achieved by all regulated entities, permit trading is only allowed between the same types of entities. In other words, a vehicle user can only trade with another vehicle user. This rule also applies to vehicle manufacturers and fuel producers. High-emission entities may need to buy more permits from the market, while low-emission entities can benefit by selling their surplus permits. The blockchain-based permit trading between the same types of entities is presented in Figure 3.

In each transaction cycle, the permit sellers/buyers can post their quantities and unit prices of permits for sale/purchase to the smart contract. This information is then written into the smart contract with a unique identification number (ID) and distributed across every node in the blockchain network, which all entities can access. In addition, the number of permits that the seller posts and the amount of tokens that the buyer wants to pay would be temporarily transferred to the account of the smart contract until the seller/buyer withdraws them or the transaction is executed.

The smart contract is triggered by addressing a transaction to it. For example, if buyer *A* sends *P* tokens to the account of the smart contract, the self-execution procedures will start. Given the ID of the permit for sale (SID), the smart contract can retrieve the seller, sale quantity, and unit price of this permit for verification. If the sale quantity (*Qs*) is greater than zero, then the transaction quantity (*Q*) is calculated and deducted from the sale quantity. In this scenario, the transaction will be successfully added to a new block with the updated permits and tokens in the accounts of both buyer *A* and seller *B*. If any other conditions occur during the verification, the transaction will be cancelled. Another example of seller *A* sending permits to the smart contract is also shown in Figure 3.

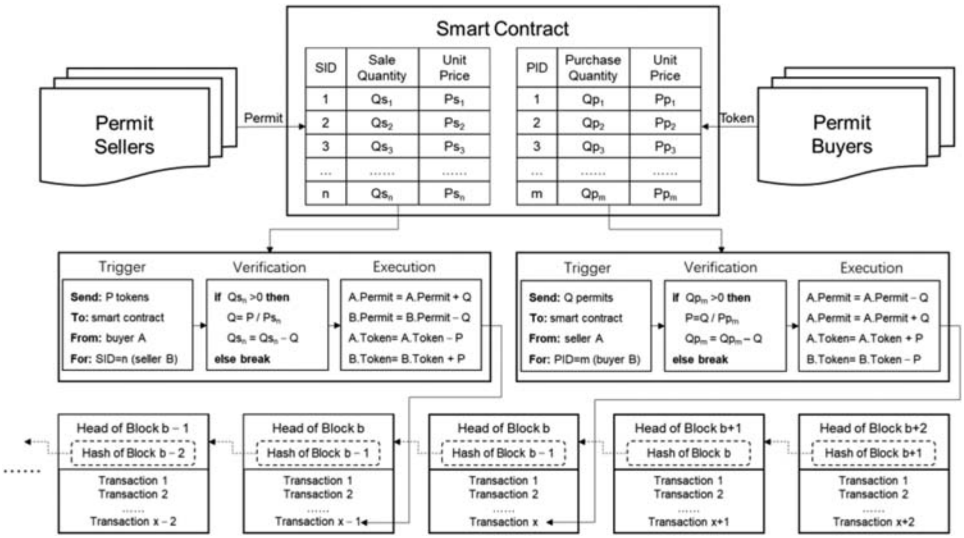

Figure 3. Schematic diagram of permit trading between the same types of entities.

3.4.2. Permit transfer from vehicle manufacturers to vehicle users

In this type of transaction, a predetermined permit is attached to each new vehicle and finally transferred from the vehicle manufacturer to the consumer when the vehicle is purchased. Transactions between vehicle users and manufacturers are also enabled by the smart contract on the blockchain, as shown in Figure 4.

Similarly, the vehicle manufacturers can post their quantities, retail prices, and permits for each type of vehicle for sale to the smart contract. If consumer *A* sends *P* tokens to the account of the smart contract for vehicle type (*n*) of manufacturer *B*, the smart contract procedures will be triggered. If the quantity of vehicle (*n*) for sale is sufficient and the consumer's payment is higher than the vehicle price, then manufacturer *B* is notified to deliver the vehicle that the consumer wants to buy. Next, external feedback (R) is needed from the consumer to confirm that s/he has received the new vehicle. Once R=1 returns to the smart contract, the permit attached to the newly purchased vehicle can be transferred from the manufacturer's account to the consumer's account on the blockchain. Meanwhile, the manufacturer will receive payment for the vehicle. If any other conditions occur during the verification, the transaction will be cancelled.

3.4.3. Permit transfer from vehicle users to fuel producers

As soon as the vehicle users refuel their cars, the corresponding permits should be transferred to the fuel producer. Meanwhile, the quantity of permits is deducted from the permit capacity of the fuel producer. Transactions between vehicle users and fuel producers are also enabled by the smart contract on the blockchain, as shown in Figure 5.

This process is similar to the permit transfer process from vehicle manufacturers to vehicle users. First, the fuel producers post their quantities, unit prices, and emission factors for each type of fuels for sale to the smart contract. If vehicle user *A* sends *P* tokens and *Q* permits to the smart contract account for fuel type (*n*) from producer *B*, the smart contract procedures will be triggered. If the quantity of fuel (*n*) for sale is sufficient and the tokens paid are equal to the permit (i.e. $P/Pf_n = Q/Ef_n$), then fuel producer *B* will release the fuel nozzle at the fuel station so that the consumer can start to refuel his/her car. When the consumer confirms that the refuelling is complete (R=1), permit *Q* will be transferred from the consumer's account to the fuel producer's account on the blockchain. Meanwhile, the quantity of permits is deducted from the fuel producer's permit capacity once the payment is received. If any other conditions occur during the verification, the transaction will be cancelled.

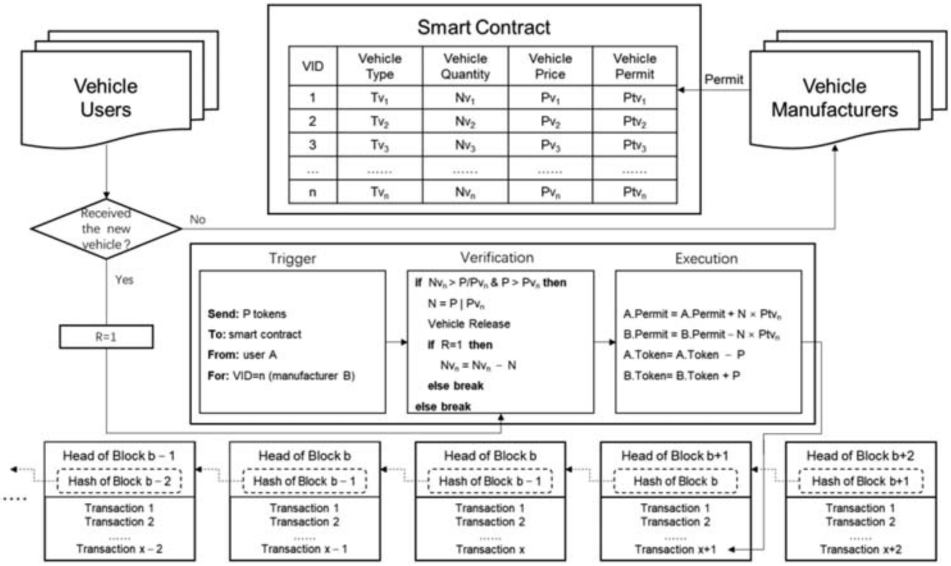

Figure 4. Schematic diagram of permit transfer from vehicle manufacturers to vehicle users.

3.5. Blockchain-based monitoring, reporting, and verification

A robust, transparent, consistent, and accurate monitoring, reporting, and verification (MRV) system for road transport CO_2 emissions is fundamental to ensure that the BC-ETS-RT operates effectively. Owing to the advantage of blockchain technology, the MRV system can be efficiently established at a relatively low cost.

As the upstream collectors of permits, the fuel producers would also be the monitors of transport CO_2 emissions. The total permits they collect are expected to be the actual CO_2 emissions in the road transport sector. In addition, each regulated entity has an account that stores the permits on the blockchain, which provides an immutable and transparent ledger of emission permits. Thus, the compliance of all entities can be ensured.

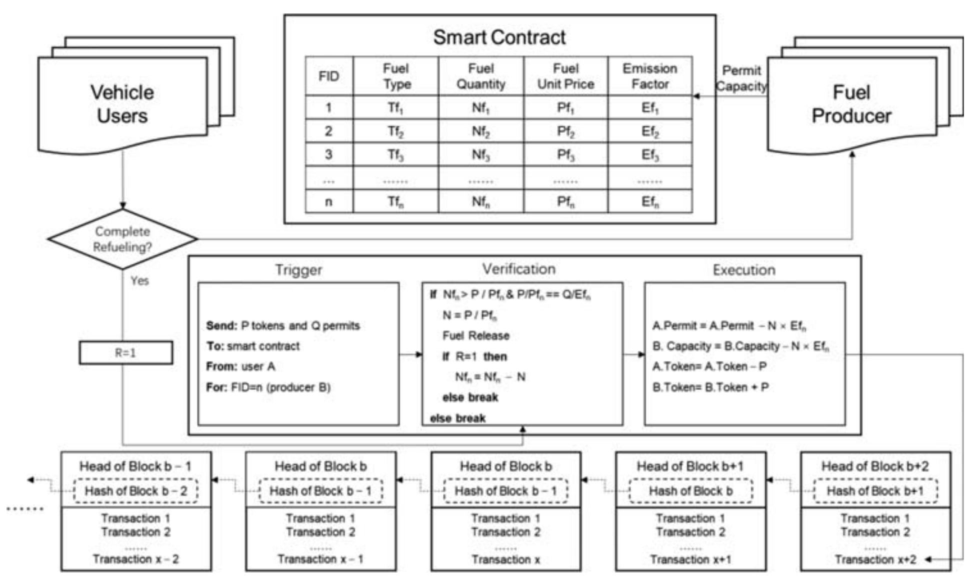

Figure 5. Schematic diagram of permit transfer from vehicle users to fuel producers.

In addition, every regulated entity is obligated to report its regulated objects on the blockchain for further verification and data collection. For example, the fuel producer should report the emission factors of the fuels before they are sold to consumers, the vehicle manufacturers should report the fuel economy of the vehicles before they are sold to consumers, and the vehicle users should report their annual VMT at the end of the target year. However, the information they report on the blockchain will be valid only when it is technically verified by a reliable and authoritative auditor.

Third-party institutions authorized by the government act as auditors to verify the authenticity of the regulated objects that entities report. In particular, the fuel emission factors of fuels and the fuel economy of vehicles need to be evaluated by well-trained professionals from the related domain. After third-party verification, the reported objects can be recorded in the smart contract on the blockchain.

4. Policy evaluation and discussion

4.1. Comparative evaluation of the policy

Since the proposed BC-ETS-RT is a forward-looking policy instrument that has never been implemented in the real world, evaluating its potential performance, acceptability and feasibility are necessary before its implementation. To evaluate and compare the proposed BC-ETS-RT and the existing upstream, midstream, and downstream ETS-RT, this study employed a multicriteria analysis method that is widely used for the quantitative evaluation of climate change mitigation policy instruments (Fu et al., 2018; Khaqqi et al., 2018; Konidari & Mavrakis, 2007). This analysis consists of three criteria supported by 11 sub-criteria that describe different aspects of those instruments. The weight coefficients and the grade scales (i.e. 0–10 corresponding to null to excellent) are adopted from Khaqqi et al. (2018) with slight modifications. The conventional ETS for non-transport sectors proposed by Khaqqi et al. (2018) is taken as the reference to comparatively evaluate the four types of ETS-RT, as shown in Table 2 below.

4.1.1. Evaluation of environmental performance

The criteria for environmental performance evaluate the overall environmental contribution of the ETS to GHG emission reductions in the road transport sector. The two sub-criteria are direct contributions to GHG emission reductions and indirect environmental effects. Both can be measured by the same indicators (e.g. changes in sectoral emissions, percentage of reduction in energy consumption, and proportion of renewable energy) and are assumed to be proportional to each other.

A conventional ETS for non-transport sectors with a cap on CO_2 emissions is graded as 7 (Khaqqi et al., 2018). Since the midstream ETS-RT is designed for vehicle manufacturers, it is similar to the conventional ETS, which is primarily designed for large firms in the power and industry sectors. Therefore, they will have the same environmental performance scores. However, the emission reduction potential of the upstream ETS-RT may be smaller since people are insensitive to the increase in fuel price resulting from the upstream ETS-RT, given inelastic demand for travel. Thus, the score of upstream ETS-RT is 6.5. On the other hand, the downstream ETS-RT, which can directly lead to cleaner vehicle use and decreased annual VMT, should have a higher score (i.e. 7.5). The proposed BC-ETS-RT, which integrates the upstream, midstream, and downstream ETS-RT, provides all options and opportunities to reduce emissions both for firms and individuals. Consequently, its score should be the highest (i.e. 8.5).

4.1.2. Evaluation of political acceptability

The criteria of political acceptability evaluate the attitudes of all involved entities towards the ETS in terms of different aspects, including static (cost) efficiency, dynamic (cost) efficiency, competitiveness, equity, flexibility, and stringency for noncompliance.

The static cost-efficiency sub-criterion measures the difference in the costs incurred by the regulated entities to reduce the targeted emissions with and without the ETS (Konidari & Mavrakis, 2007). A good grade (i.e. 7) is given as the base score for the conventional ETS. In the upstream ETS-RT, most of the fuel producers transfer the permit cost to the consumer by increasing the fuel price. Thus, the cost efficiency score (i.e. 7.5) of the upstream ETS-RT is better than the base score. The downstream ETS-RT may lead to additional financial burdens for those

Table 2. Multicriteria Evaluation of different types of ETS.

Criteria	Weight	Sub-criteria	Weight	Conventional ETS (non-transport)	Upstream ETS-RT	Midstream ETS-RT	Downstream ETS-RT	BC-ETS-RT
Environmental Performance	0.168	Direct contribution to GHG emission reductions	0.833	7	6.5	7	7.5	**8.5**
		Indirect environmental effects	0.167	7	6.5	7	7.5	**8.5**
Political Acceptability	0.738	Static cost efficiency	0.474	7	**7.5**	7	6.5	7
		Dynamic cost efficiency	0.183	6	5.5	6	6.5	**8.5**
		Competitiveness	0.085	5	**6**	5	4	5
		Equity	0.175	7	6.5	7	7.5	**8.5**
		Flexibility	0.051	7	6	7	8	**9**
		Stringency for noncompliance	0.032	5	6	5	4	9
Feasibility of Implementation	0.094	Implementation network capacity	0.309	7	**7.5**	7	6	7
		Administrative feasibility	0.581	7	**7.5**	7	6	7
		Financial feasibility	0.110	7	**7.5**	7	6	7
Weighted Total Score				6.69	6.75	6.69	6.59	7.64

individuals who travel more or drive high-emission cars. Therefore, the downstream score should be worse (i.e. 6.5). Since the proposed BC-ETS-RT integrates the upstream, midstream, and downstream ETS-RT, its score should be neutral (i.e. 7).

The dynamic cost-efficiency sub-criterion measures the ability of the ETS to support any research, development, investment, and innovation of emerging technologies for emission abatement (Creutzig et al., 2011). Since the options for fuel producers to reduce emissions are very limited in the upstream ETS-RT, its dynamic cost efficiency should be worse than that of the conventional ETS. However, the opportunities for the midstream and downstream ETS-RT are diversified, such as improvements in fuel economy and the adoption of electric vehicles. Since the proposed BC-ETS-RT could provide all these opportunities for the involved entities, its score is much higher (i.e. 8.5).

The competitiveness sub-criterion measures the capacity of regulated entities in the ETS to compete with other entities via price, products, or service attributes. All forms of ETS will affect the entities' production costs. Some entities (e.g. fuel producers) can transfer the cost to the customers, while some (e.g. vehicle users) cannot. Therefore, the competitiveness score of the upstream ETS-RT (i.e. 6) is usually higher than that of the downstream ETS-RT (i.e. 4). Similar to the analysis of the static cost-efficiency sub-criterion, the scores of the midstream ETS-RT and the proposed BC-ETS-RT are neutral (i.e. 5).

The equity sub-criterion evaluates the fairness of the permit allocation, compliance cost, and reduction responsibility. The three types of entities have different responsibilities for emission reduction in the road transport sector. As the direct emitters of transport emissions, vehicle users should be the first choice for the regulated entities. Since the vehicles produced and sold by vehicle manufacturers are the sources of emissions, the vehicle manufacturers are the second candidates to hold permits. In addition, the fuel producers are responsible for emissions reduction, since most CO_2 emissions come from burning the fuels they sell. Consequently, the equity scores of the upstream, midstream and downstream ETS-RT should be increasing (i.e. 6.5, 7, and 7.5, respectively). Given that the proposed BC-ETS-RT involves all types of entities, fuel producers, vehicle manufacturers, and vehicle users, its equity score is significantly enhanced (i.e. 8.5).

The flexibility sub-criterion measures the ability to provide different compliance options for the regulated entities to achieve emission reduction goals. Since the numbers of compliance options for fuel producers, vehicle manufacturers, and vehicle users are increasing, the flexibility scores for the upstream, midstream and downstream ETS-RT are also increasing (i.e. 6, 7, and 8, respectively). The proposed BC-ETS-RT can provide all of these compliance options so that its flexibility score is the highest (i.e. 9).

The stringency for noncompliance sub-criterion measures the rigidity of the ETS's provisions towards regulated entities that fail to comply or do not participate. For the upstream ETS-RT, the number of regulated entities is relatively small, so deterring noncompliance is easy. In contrast, the downstream ETS-RT contains millions of regulated entities that make MRV of the emissions very difficult. Given its automation, transparency, and immutability features, the blockchain-supported ETS is superior to the conventional ETS. Thus, the proposed BC-ETS-RT is assigned a high score (i.e. 9).

4.1.3. Evaluation of the feasibility of implementation

The feasibility of implementation criterion reflects how well the ETS could be implemented with the required infrastructure and legal framework, which is based on the following three sub-criteria.

The first sub-criterion is the implementation network capacity, which evaluates the technological infrastructure, trained personnel, data credibility, and information transparency of the ETS. Compared with the conventional ETS, the upstream ETS-RT involves fewer regulated entities and requires less infrastructure, while the downstream ETS-RT is the opposite. The proposed BC-ETS-RT, in turn, needs additional support in technological infrastructure but less personnel support. Overall, its score is therefore neutral (i.e. 7).

The second sub-criterion is administrative feasibility, which measures the amount of work required by the regulatory institutions to implement the ETS. For the conventional ETS, the amount of work is mainly based on the number of regulated entities involved. Thus, the administrative feasibility scores of the upstream, midstream and downstream ETS-RT are decreasing (i.e. 7.5, 7, and 6, respectively). Although the proposed BC-ETS-RT consists of additional entities, most of its work relies on machines, smart devices, and developed algorithms. Therefore, its score of administrative feasibility is not affected by the large number of entities (i.e. 7).

The third sub-criterion is financial feasibility, which measures the overall cost of implementation, including costs of preparation, administration, reporting, and operation. This sub-criterion is similar to administrative feasibility, which is proportional to the number of regulated entities involved. For example, the downstream ETS-RT has the lowest score of financial feasibility (i.e. 6) due to the large number of vehicle users. The proposed BC-ETS-RT may lead to higher costs in setting up the infrastructure needed for implementation, but the automation process on the blockchain will lower the costs of administration, reporting, and operation. Given this offset, a score of 7 is assigned to the BC-ETS-RT.

4.2. Policy effectiveness

In the proposed BC-ETS-RT, all regulated entities from upstream, midstream, and downstream can collaborate to achieve the optimization of all three determinants of CO_2 emissions in the road transport sector. Thus, the effectiveness and efficiency of the policy can be maximized.

For vehicle users: Once the BC-ETS-RT is implemented, the environmental attributes (e.g. certified emission reductions, carbon offsets, renewable energy certificates) can be easily attached to the permits of the vehicle users, thereby allowing users to digitally link their decisions on car choice, vehicle miles, and fuel purchase with corresponding financial benefits. For example, individuals or transportation companies with high-emission vehicles may consume their permits faster. Thus, they may need to pay for additional permits, which can provide a financial incentive to choose low-emission vehicles or reduce their VMT. This may help accelerate the low-carbon transition of road transport.

For vehicle manufacturers: There is a stricter emission cap on new entrant vehicles, which are attached with specific initial emission permits. However, vehicle manufacturers can adjust the initial permit of each new vehicle in a certain range based on fuel economy. For example, if a vehicle manufacturer produces a type of vehicle with a better fuel economy than the average level, then the initial permit of this new vehicle can be decreased so that more vehicles can be sold. However, the initial permits of new vehicles must satisfy the travel demand of an average VMT among all users. As a result, vehicle manufacturers are motivated to improve the fuel economy of vehicles to increase sales and profits. In this case, existing financial subsidies to promote electric vehicles could be replaced, leading to expenditure savings for the government.

For fuel producers: The permitted capacity for fuel producers determines the amount of fuel that they can produce. If they choose to use more low-carbon fuels (e.g. bio-diesel, ethanol fuel, natural gas, etc.) and reduce the fuel emission factors, they can sell more or gain financial benefits through trading the remaining permit capacity. In addition, fuels with lower emission factors may be more attractive to consumers restricted by the permits, thereby reducing road transport emissions.

4.3. Potential concerns

Although there are many advantages provided by the BC-ETS-RT, we should also pay attention to some concerns about the blockchain. First, the activity and emission data recorded on the blockchain for the purpose of MRV may be sensitive for stakeholders, such as the involved individuals, corporates, and governments. It is necessary to enable authority management and multi-channels on the blockchain so that only the members with a registered certificate can access the specific data on the blockchain. Therefore, a consortium blockchain or hybrid of private and public blockchain may provide the required technical solutions, such as the Hyperledger, which is a blockchain platform for enterprises.

Second, the environmental impacts of running the blockchain solution for the BC-ETS-RT should also be taken into account. For example, if the Proof of Work is adopted for the consensus mechanism of the blockchain, a certain amount of computational effort is required to protect the blockchain from tampering and attack (Nakamoto, 2008). This process consumes a significant amount of energy in the form of electricity. In this case, a more efficient consensus mechanism should be introduced, such as the Proof of Stake, Delegated Proof of Stake, or Practical Byzantine Fault Tolerance (Sankar et al., 2017).

Third, the transaction efficiency of a large number of entities on the blockchain should be further tested and verified, since most blockchain platforms have limitations in scalability, latency, and throughput. For example, the current TPS (Transactions Per Second) rate of the Hyperledger is approximately 3,000 (Dhillon et al., 2017). In the future, a faster system should be developed and actual operational data should be incorporated into the system to evaluate whether it can meet the transaction volume requirements.

5. Conclusions and future research directions

This paper proposed a blockchain-based ETS for road transport (BC-ETS-RT), integrating upstream, midstream, and downstream ETS-RT. In the proposed BC-ETS-RT, the government determines the cap and allocates the initial permits for CO_2 emissions in the road transport sector, while all the fuel producers, vehicle users, and vehicle manufacturers are involved as regulated entities with tradable permits. As a result, the BC-ETS-RT can optimize all three determinants of CO_2 emissions in the road transport sector: fuel emission factors, vehicle fuel economy, and VMT, respectively. Driven by the blockchain, all the emission permit transactions and MRV are automatically executed and recorded on a decentralized, distributed, and public digital ledger instead of being managed by experts and institutions, which dramatically reduces the cost of administration. This system can also guarantee transparency and address possible double counting and fraud. In addition, the blockchain could enable peer-to-peer trading on a mutually distributed network that allows for high-level trust among users. The blockchain-based MRV could also provide an accounting ledger for activity in relation to relevant articles under the Paris Agreement (Rogelj et al., 2016), which includes requirements that all parties report regularly regarding their emissions and their implementation efforts. Therefore, collective progress towards achieving the purpose of the agreement can be better assessed.

A multicriteria analysis method was adopted to evaluate the proposed BC-ETS-RT in comparison with other ETS options. The results show that the proposed BC-ETS-RT performs better than all other ETSs with respect to the weighted total score because it can incorporate the advantages and avoid the disadvantages of existing systems by integrating the upstream, midstream, and downstream ETS-RT enhanced by the blockchain technology. The possible effects of the BC-ETS-RT were further discussed, indicating that the regulated entities can obtain financial incentives from permit trading if they participate in emissions reduction. With all fuel producers, vehicle users, and vehicle manufacturers collaborating on compliance, the effectiveness and efficiency of the emission abatement can be maximized. Therefore, the proposed BC-ETS-RT may be the most effective instrument to limit road transport emissions.

However, there are several limitations in the current study that motivate future research directions. First, this paper mainly focused on the policy design and evaluation of the BC-ETS-RT. The behavioural responses of different regulated entities should be further investigated based on multiagent modelling and simulation in future research. Second, the proposed policy framework currently only covers on-road vehicle emissions, not including the non-vehicle emissions in the road transport sector, such as the emissions of vehicle/fuel production, transport, and scrapping, as well as emissions from lighting, maintenance, inspection, or disposal of the infrastructures (e.g. roads, parking lots, bus stations and depots). Those non-vehicle emissions can also be easily tracked using blockchain technology, which should be further considered in the future.

Note

1. On-road CO_2 emission only, excluding the 'well to tank' and other indirect emissions.

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