Conceptual framework for the interactions between conventional and Alternative Fuel vehicles in the energy transition.

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ABSTRACT

Challenges such as global warming, depleting reserves and threats to energy security necessitates a transition. According to the IEA, the transport sector is one of the major culprits accounting for 24% of global emissions where light-duty vehicles and two and three wheelers account for 48% (3.5 BtCO2) of this. Hence, a transition in this subsector would greatly contribute to global combat against climate change. However, transitions in transport have existed since the earliest appearance of more modern and efficient alternatives to the horse carriages and dominance of one Powertrain against others have been subject to certain factors influencing their interactions. This study adopts systems thinking approach to identify the most influencing factors and presents a conceptual framework that demonstrates the interactions between the most promising powertrains. The factors cut across economic, social and technical factors and other crosscutting issues such as inter-power-train competition and spillover effects. Quantification and application of this framework is also recommended.

Keywords: System thinking, Electric Cars, alternative fuel vehicles, Energy Transition, Transport

1 Introduction

Global dependence on fossil fuels and their related products has led to energy and environmental sustainability problems, such as depleting reserves, energy security issues, and global warming resulting from greenhouse gas emissions (GHG). The transport sector is one of the major culprits responsible for this, accounting for 29% of total final energy consumption and 24% of global CO_2 emissions in 2019 (IEA, 2020b). Furthermore, figure 1 shows that CO_2 emissions from light-duty vehicles and two and three wheelers accounted for 48% (3.5 $BtCO_2$) of total emissions from transport sector while heavy trucks accounted for 25% (1.8$BtCO_2$) of transport emissions. This necessitates a focus on decarbonization of the light and heavy-duty subsectors for significant results in the transport sector.

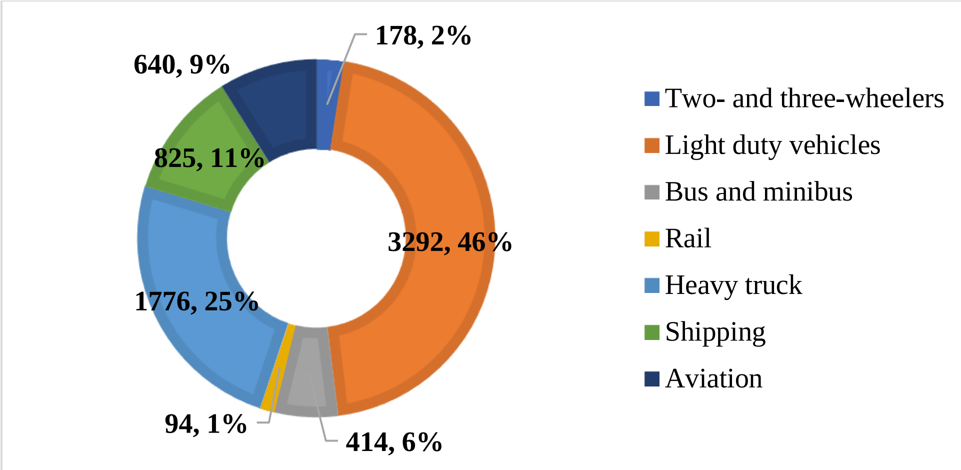

Figure 1: **Global CO2 emissions from transport by Sub-sector(MtCO2)** (IEA, 2022)**.**

Transport sector decarbonisation implies replacing hydrocarbon-based fuels with low or zero carbon fuels such as electricity, hydrogen or synthetic fuels. The substitution may also require substitution of the energy converters from the dominant internal combustion engines to alternatives. The internal combustion engine (ICE) is the most prevalent propulsion system in the transport sector today comprising gasoline and diesel engines. In reality, the ICE does not constitute a problem if the fuel source is clean. However, there is a need to transition away from this to cleaner propulsion systems, consequently implying transitioning to cleaner fuels as well. The authors proposed several alternative propulsion systems to the ICE. The fuel cell vehicle is propelled by energy produced from the reaction between hydrogen and oxygen in a fuel cell, which can charge a battery in the case of a range-extender (hybrid FCEV) or directly propel the vehicle (FCEV). The most dominant fuel cell technology is the proton-exchange membrane fuel cell (PEMFC), while Brazil has been exploring the potential of the solid-oxide fuel cell (SOFC) electric vehicle, which can power biofuels like ethanol without needing hydrogen production. On the other hand, battery-electric vehicles (BEV) are propelled by batteries, of which lithium-ion batteries are the most common today. Hybrid electric vehicles (HEV) combine electric motors powered by batteries with internal combustion engines (ICE) to improve vehicle efficiency. A generator driven by the internal combustion engine and regenerative braking charges the batteries. A variant of HEV is the Plug-in Hybrid Electric Vehicle (PHEV), which powers its batteries from the grid besides charging from regenerative braking and ICE. HEVs are viewed as intermediate propulsion technologies between ICEs and EVs. (Yamamura et al., 2022). On the other hand, as stated in the foregoing, the potential energy carriers for the transport sector transition include liquid and gaseous carbon-based electrofuels, hydrogen and electricity. However, there still exists significant uncertainty to what extent they would provide a solution to the future of transport.

The introductions of these technologies to compete with the dominant Powertrain is not new to the sector except for the hydrogen fuel cell vehicle. However, technology alone does not determine the transition to alternative powertrains and fuels. Hence, It is important to evaluate factors and interactions which influence the diffusion of alternative fuel vehicles (AFV) and the energy transition (Yamamura et al., 2022). Markard et al. (2012) posit that the transport sector is a socio-technical system and comprise a network of actors, institutions, material artefacts and knowledge which interact with one another, therefore, a transition in this sector would imply dynamic changes across different dimensions: technological, material, economic, organizational, institutional, political and socio-cultural and over long time-spans. This would result in the emergence of new products, services organizations and business models to complement and/or substitute existing ones. Thus, a transition to cleaner propulsion systems will require the complementary development and penetration of new Powertrain technologies, infrastructure, fuel supply systems, user practices, etc.

The penetration of newer powertrain alternatives would imply a competition between existing and new powertrains and implicitly fuels. This competition is inherent because of the limitations of market demand, production resources and consumer decisions. Several studies explore the competition between powertrains such as Phirouzabadi et al. (2020) which demonstrated that the penetration of a powertrain is depending on the interactions (inhibitive or support) with other powertrains. Therefore, this contribution aims to propose a conceptual framework that describes the interactions between competing Powertrain technologies, identify the influencing factors from hindsight (history) and literature studies that determine the diffusion of these technologies and how to leverage them for to enable a just transition in the transport sector to cleaner fuels and powertrains. The remainder of the paper includes literature of the history of transitions in the transport sector and diffusion studies in section 2, while section 3 presents the method adopted for this study, section 4 provides a description of the conceptual framework and section 5 concludes the paper.

2 Literature review

2.1 History of transitions in the transport

Transitions in the transport sector began with a stiff competition between various mobility options in the late nineteenth century such as the horse carriages, steam engines, the internal combustion and the electric vehicle. However, the earliest dominant Powertrain technology after the horse carriages were the electric vehicles (EV), which has been around for over 150 yrs. It was way ahead of the gasoline internal combustion engine vehicle and dominated the market with a ratio of 3:1 in the early 1920s. The EV was seen as the "environmentally friendly family's second car for the affluent". However, in the 1930s, the gasoline vehicle took over market dominance due to the gasoline vehicles' technology maturity and cost advantage over the electric vehicle. The Gasoline vehicle took over as the leader and surpassed electric vehicle both in market penetration, performance and cost. This was largely resultant of gasoline supply infrastructure improvement, small retail establishments, related skill labor availability, inexpensive and portable fuel and users demand for longer distance travel that was never able to be met by electric vehicle because of their limited battery capacities, (J. Santini, 2011; Shepherd et al., 2012; Struben & Sterman, 2008; Yu et al., 2011)

Some of the technology improvement of the gasoline vehicle, which fostered its market dominance, was the development of the electric starter and the spillover effects from electric vehicles such as bias-ply tire, which improved its performances against its electric vehicle counterpart. The electric starter produced higher cranking power, allowing reliable engine starting and a much higher compression ratio, enabling more efficient gasoline engines. In addition, to engine efficiency, higher average speed, good roads made from gasoline taxes, combination of electrical and mechanical features, good tires and reduced ground clearance were factors that resulted in the failure of the initial appearance of the electric vehicle (J. Santini, 2011).

Rising oil prices and environmental concerns mainly in the US led to renewed interest in electric vehicles in the mid-1990s. This resulted in companies like General Motors (GM) mass-producing in the Electric vehicle. However, this was also short-lived due to profitability concerns. Renewed interest in EVs has been evidenced by several policies and EV production commitments from existing and new automakers to promote the electrification of transport. In addition, there has been a rapid growth of in new manufactures, production, and interest of incumbents in the last decade, resulting in a global EV stock of 16.5 million vehicles as of 2021 (IEA, 2020a; Yu et al., 2011).

The future of EVs may be different this time in considering global push for cleaner transport modes, rising cost of fuels and other political and economic factors. However, the challenge for new alternative Powertrain technologies is greater now, as there exists a mature oil industry, fully articulated infrastructure, powerful stakes and global sociotechnical system tightly bound to the internal combustion engine. Other important feedbacks include vehicle improvements and cost reductions driven by economies of scale, research and development, learning by doing, and field experience, all improving the ICE vehicle performance, sales, revenue, scale, and experience still further. In addition, Word of mouth and marketing stimulate awareness and adoption, boosting revenue and the installed base of new vehicles, generating still more word of mouth and marketing expenditure. (Struben & Sterman, 2008).

Lixin (2009) posits that factors such as the rise of new original equipment manufacturers (OEM), rising gasoline prices, exploration of new business models, growing consumer awareness, growing Cooperation in charge station and infrastructure development, market approach and improvement in battery storage and management technologies would make the future of EVs different from the earlier appearances. Yu et al. (2011) also states that the widespread reintroduction of electric vehicles greatly affect the industry, leading to a significant reconfiguration of the existing structure. These changes would involve significant modifications in the industrial production chain (its participants and their inter-relationships), supply infrastructure and energy matrix, new business models, marketing, vehicle ownership models, as well as institutional relations and government policies. The transition would also imply a shift from fuels to minerals.

2.2 Alternative Fuel Vehicle diffusion studies

Several studies explore the diffusion of alternative fuel vehicles (AFV) to identify the factors that would influence the diffusion. Most studies are focused on national and municipal scale. However, Yamamura et al. (2022) postulate that the global diffusion of electric vehicles, especially to developing countries, would be subject to the emergence of a dominant design. This implies that the learning rate of AFVs would influence their diffusion.

Mazur et al. (2018) applied systems dynamics to investigate customer choice between various vehicle types. The study demonstrated that improvement in fuel cell technologies and batteries decreased cost and improved consumer adoption in the short-term. In addition, alleviation of the range anxiety and infrastructure availability concerns would improve the position of BEVs and FCEVs and introduction of autonomous driving had the greatest impact on GHG reduction. Similarly, Park et al. (2011) developed a market penetration model for hydrogen fuel cell vehicles based on a generalized model combining systems dynamics and the Bass Diffusion model. The study indicated that imitation and innovation factor have direct influences on the time before reaching critical mass and market. Prices of HFCVs and availability of refueling stations influenced imitation and adoption rate.

An analysis of the market for new energy vehicle in China over 60 years using systems dynamics based on Lotka-Volterra model was performed by Sun & Wang (2018). The authors defined variables such as market scale, number of charging infrastructure, per capita disposable income, vehicle prices, vehicle technology and fuel consumption, and associated rate variables. The study demonstrated that governmental subsidies, infrastructure improvement and technology development, which affected cost, convenience, guaranteed long-term rapid NEV adoption. For Brazil, Benvenutti et al. (2017) combined the Bass diffusion model and systems dynamics to test the effectiveness of certain policies related with import duties, motor vehicles, property tax, tax on manufacturing goods, conventional car sales ban form 2030. The authors found policy incentives were necessary to promote higher diffusion of AFVs in the country. However, the study did not consider infrastructure development, power demand growth compared to the power generation capacity expansion plan.

On a global scale, the dynamics influences between conventional, electric and hybrid powertrains was explored by Mirzadeh Phirouzabadi et al. (2020). Applying a technological innovation framework (TIF), the authors discovered growing popularity of electric vehicles among powertrains and that the powertrains interacted differently at different episodes of the development, including competition, parasitism and commensalism. Juniper, et al. (2020) corroborates this study and finds that HEVs and BEVs crowd out the ICEV. However, overlaps in the socio-technical interactions between the powertrains may result in negative or positive externalities between them. The authors also posit that endogenous (e.g. attractiveness or carrying capacity) and exogenous factors (e.g. financial crisis or fuel price fluctuations) influences changing behaviors. However, the study did not explicitly explore their impact on the changing behaviors.

Struben & Sterman (2008) developed a behavioral, dynamic model to explore the possible transition from ICE to AFVs such as hybrids, CNG, biofuels, and HFCVs. The author's postulates that a self-sustaining adoption of alternative fuel vehicles would require several decades due to the long lifecycles of vehicles and that diffusion would be slow in the absence of high oil prices and large subsides. Strong word of mouth and marketing tend to favor diffusion. The effect is minimal compared to the lifecycles of the AFVs. In addition, the authors proposed destruction of used ICEVs instead of trade-ins and stimulating social exposure, learning and positive feedback by increasing installed based led to rapid adoption. The study does not capture the impact of oil price on Powertrain diffusion, as oil prices have risen significantly higher than the earlier appearance of the electric vehicle. Other recommended areas of research include estimating the impact of marketing, direct social exposure, and indirect word of mouth on the consideration set and consumer choice, disaggregation of vehicle features and performance and. Interactions with other industries and the fuel supply chain.

The study by Pillay et al. (2020) to quantify the impacts of EVs penetration and their relevance in South Africa to reach GHG emission target indicated that price factor for vehicles and disposable income are significant factors in determining EV penetration. Hence, greater personal wealth resulted in greater transportation demand and vehicle purchase.

3 Methodology

The method applied in this research is systems thinking, an aspect of systems dynamics modeling. Jay W. Forrester developed this method in his book ''Industrial Dynamics''. It involves the study of the policies and decision making on system control and the structural characteristics of systems, based on several unique features in the method (Park et al., 2011).

Systems thinking and system dynamics approaches are used to address complexity in systems. Systems thinking represents qualitative modeling, where the end goal is to develop a conceptual model that presents the dynamic interaction between system components an enable informed decision making. The key tool for systems thinking is the causal loop diagram (CLD). This is useful for representing mental models indicating the feedback structure, which determines the dynamic lever of the system. In addition, the feedback structure provides opportunities to find root causes of dynamic changes. This structure refers to the closed circuit generated by the interconnection of the causal sequences of the variables. The CLD consists of a set of nodes and edges, which demonstrates the interrelationship between different variables in a system. The Nodes represent the variables and edges are the links that represent a cause-and-effect relationship between two given variables. The links have polarities that represent a change either in the same or in the opposite direction (Ghisolfi et al., 2022; Yusaf et al., 2022).

The feedback structure of the CLDs is composed of feedback loops. These loops can be either reinforcing loops denoted by "R or +" or Balancing loops denoted by "B or –". The reinforcing loop indicate the strengthening of a change in a direction, which implies exponential growth. On the other hand, the balancing loop indicates that a change in a direction can be reversed in the opposite direction to create a balancing effect. This behavior leads to a goal-seeking or control behavior of the system (Ghisolfi et al., 2022).

One of the goals of CLDs is to identify the dynamic levers that can lead to significant improvements in the system. CLDs identify these dynamic levers as the core symptoms, critical variables, points of interventions, tipping points or simply areas where interventions are deemed most effective where a small and well-focused actions can produce a big change. The leverage points in a system range from physical elements (i.e., indicators, structures, delays) with the weakest leverage, information and controls (i.e., balancing/reinforcing loops, rules) with medium leverage, and to ideas behind the system (i.e., goals) with the strongest leverage. Therefore, dynamic levers can be identified as variables that are: (1) a common cause of multiple effects that can accelerate or decelerate the operation of a system; (2) an intervener can influence, leading the system to major changes; (3) are the root cause characterized by being independent, generating significant and irreversible changes that occur when thresholds have been reached (Ghisolfi et al., 2022).

In this study, literature review of diffusion studies and historical studies on transition in transportation was performed to identify dynamic levers that influence transition and the interactions between competing alternatives, which resulted in a development of a conceptual causal framework. According Meadows as cited in Ghisolfi et al. (2022), "Dynamic levers can be understood as core symptoms, critical variables, points of intervention, tipping points, or simply areas where interventions are deemed most effective, where a small shift in one thing can produce a big change in everything". Hence, the conceptual causal framework developed here in identifies the critical points of interventions and variables that result in significant effect in the transport sector transition.]

Model Boundary conditions and Parameters

The model boundary chart for this study is shown in Table 1, and lists exogenous variables (not affected by the state/ feedback loops of the model), endogenous variables (dependent on the system state) and decision criteria.

Table 1: Model Boundary chart

Endogenous	Exogenous	Decision criteria
• Emission factors for CO_2, NOx and SOx for all Technology type	• Powertrain lifespan	• Market share of AFVs
• Fuel demand and supply	• Population	• Emission reduction
• Oil Price	• GDP, disposable income	• Conservation of critical minerals
• Range		
• Vehicle population		
• Investments in Alternative Fuel vehicles.		
• Investment in energy supply infrastructures		
• Primary resource/minerals demand		
• Mineral Reserves		
• Infrastructure		

4 Conceptual framework of the interactions between the ICEV and AFV

It is important to contextualize the transition in the transport sector as this would imply competition between the dominant gasoline ICEV, gasoline fuel and its supply infrastructure and alternative competitors. Competition between alternative powertrains has existed from the earliest appearance of alternatives to horse carriages and to the current dominance of the gasoline ICEV. The dominance of the ICEV resulting in an established supply infrastructure, significant investments and vested interests in the oil sector makes a transition or substitution from oil difficult. However, as in the past, petroleum consumption gained dominance with the widespread development and adoption of the motor vehicle, making petroleum heavily dependent on transportation. Thus, it is important to investigate the interactions and factors influencing the transport sector's transition, as they address the influencing factors associated with the interactions between the incumbent gasoline vehicle and alternatives, as shown in figure 2.

The causal loop diagram in figure 2 shows the framework for understanding the interactions between competing technologies. The framework identifies both endogenous and exogenous factors influencing their interactions. The competition considered in this between the gasoline ICEV, electric vehicle and hydrogen fuel cell vehicles. The market potential capacity for all competing vehicle technologies is dependent on population growth and forms the basis from which the populations of ICEV and AFVs can be composed of. The gasoline ICEV population/market scale is influenced by the global market potential, which reinforces the growth rate potential. The cost factor and availability of refueling infrastructure also influenced the growth rate. The cost factor is a weighted function of initial purchase cost and operational costs of the vehicle, which includes fueling costs, maintenance costs, etc.

Oil price is one of the most significant factors, which resulted in the reappearance of EVs in the mid-1990s, and as shown in figure 3, this has been high since early today's resulting in the rapid growth of electric vehicle population. This presents an opportunity for AFVs to “ride the tide” towards substituting of oil for transport purpose.

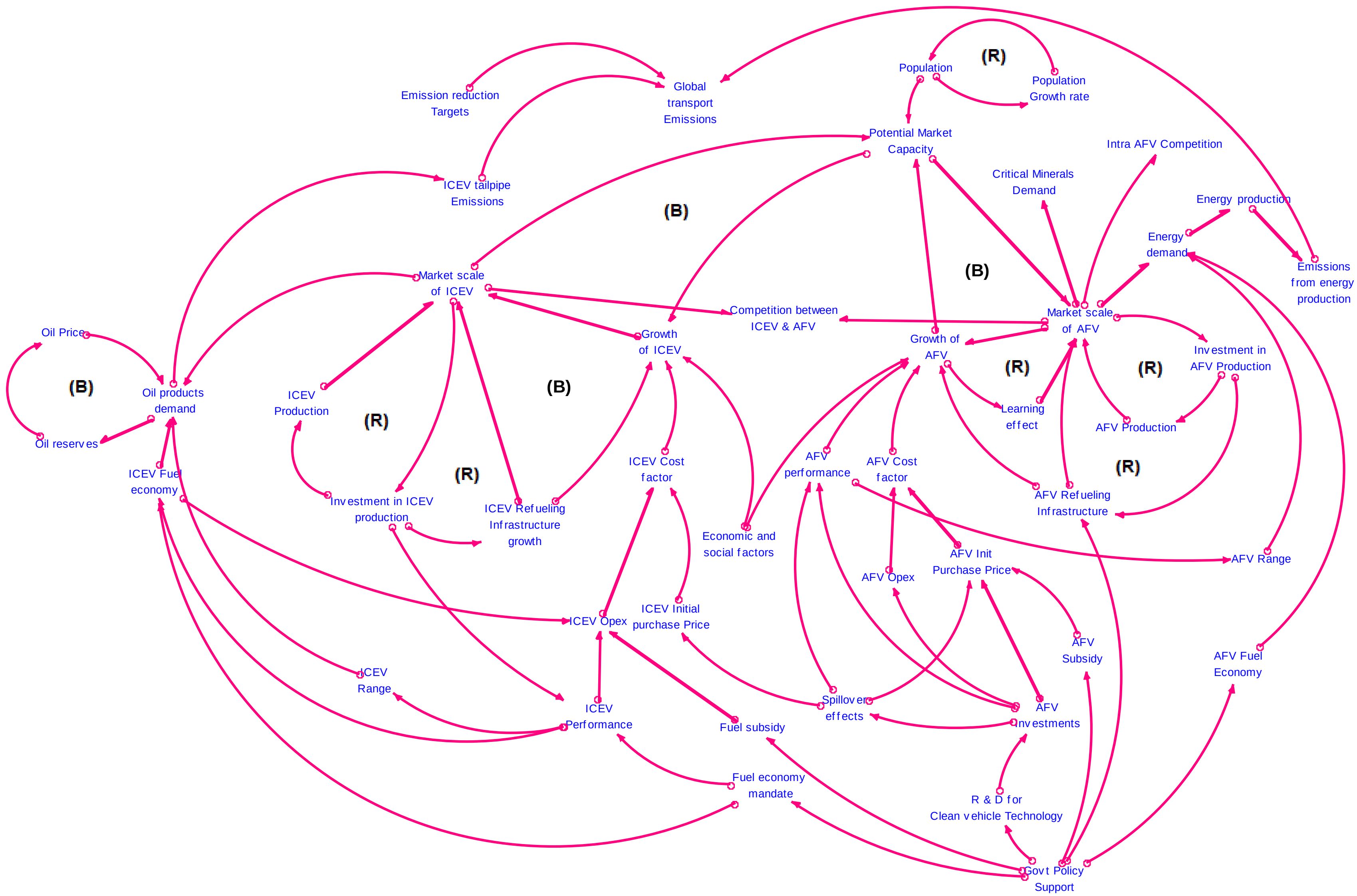

Figure 2: Conceptual framework for the competition between Gasoline ICEV, Electric Vehicles and Hydrogen FCEV

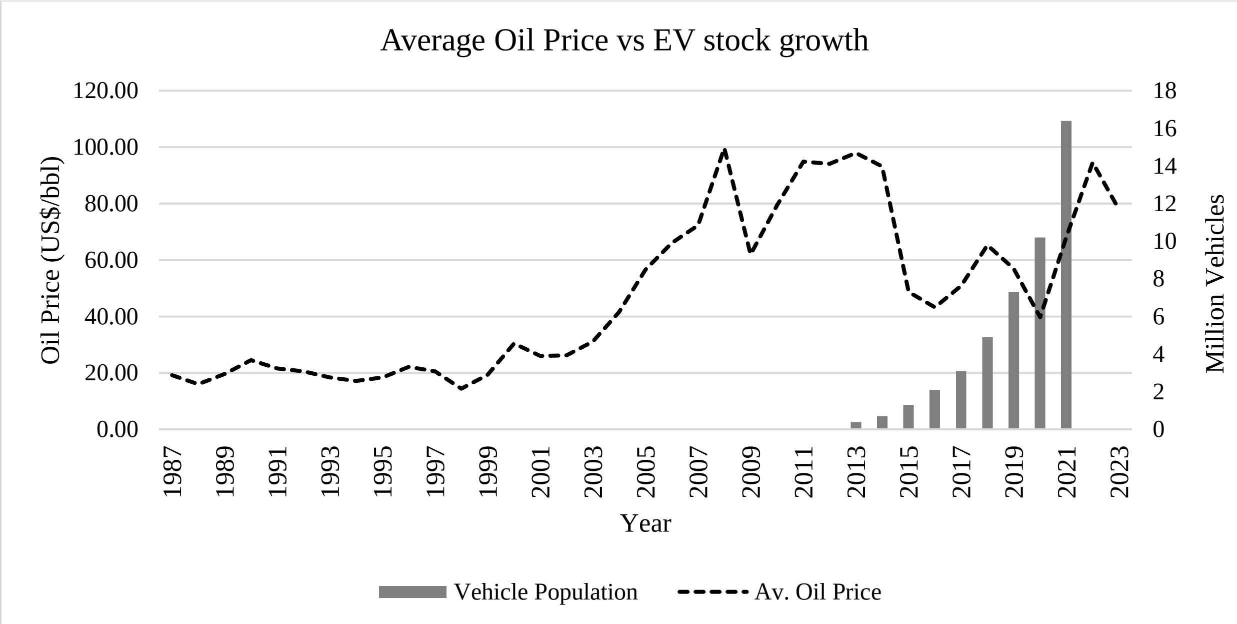

Figure 3: Average Oil Price Vs EV stock growth (IEA, 2020a; macrotrends, 2023)

Figure 4 shows the causal relations between oil price and growth of the ICEV. Oil prices affect fuel prices and the operating costs of ICEVs. This influences the attractiveness of the ICEV and, by consequence, the market scale that affects the fuel demand and supply.

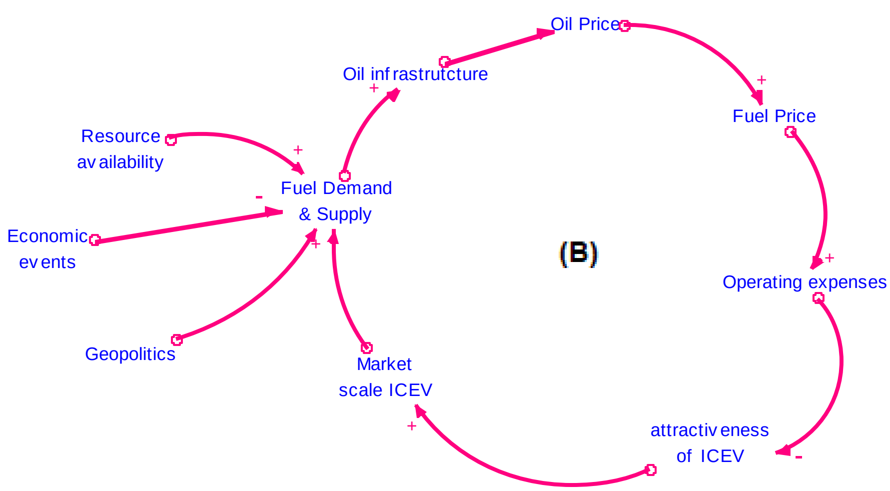

Figure 4: Causal loop diagram of oil price impact on ICEV market scale

Forces of demand and supply resulting from global economic, resource availability or geopolitical events influence the price of petroleum in the market as greater demand would cause a rise in oil price and oversupply of oil than demand could also result in low oil prices. Furthermore, demand growth would also result in investment in new oil infrastructure, thereby reinforcing the dominance of the oil regime while reduction in demand by adoption of alternative technologies and fuels would may result in decommissioning or oil assets.

Fuel economy mandates aimed at improving efficiency, limiting emissions, and reducing fuel consumption would result in reduced operational costs such as fueling and maintenance costs, energy demand and by extension tail pipe emissions, making ICEVs more competitive. In addition, improved efficiency of the ICEV results in enhanced performance. The growth in market scale catalyzes investment in vehicle production, which reinforces ICEV production and availability. This catalyzes investment in refueling stations.

Alternative Fuel Vehicles (BEV and HFCV) competes with the ICEV for global market potential. The growth rate of AFVs also influences its market scale. However, the recency of the AFV makes its growth subject to learning rate with growth of market scale. The growth in the market scale of AFVs spurs investment in AFV production, increased production capacity and number of refueling stations to meet corresponding fuel demand. On the other hand, AFV costs have been a barrier to rapid diffusion in the transport sector up to now; however, in recent times, costs have been dwindling due to economies of scale gained over the years and is expected to further decline. This decline would be due to investment in research and development of more efficient and cheaper battery chemistries, in addition to governmental subsidy programs for alternative fuel vehicles. The AFVs performance and operational costs also improve with AFV development. Growth in AFV market scale implied increased energy demand, which affects the production capacity requirement, mix and associated emissions. Both ICEV and AFV emissions contribute to global emissions but limited by emission reduction targets. This would also indirectly affect the vehicle population and mix.

External factors: Government policies regarding market regulations, fuel and vehicle standards, emission targets, taxes, infrastructure development, clean technology research and development support, and incentives are the most impactful external factors that could support the transition to cleaner transport. (Claudio Seitz, 2014).

Crosscutting factors: Crosscutting factors such as the Spillover effects among Powertrain technologies could have reinforced effects on the dominant technology over newer Powertrain technologies and possibly provide an established platform for new Powertrain technologies to thrive. For example, the spillover effects from EV such as development of lighter vehicle bodies for improved performance, could further improve the performance of the gasoline ICEV. On the other hand, dominant designs from incumbent Powertrain that are partly or unrelated to the vehicle energy systems are being adopted by newer powertrains. This factor was one of the most important factors that aided the takeover of the ICEV. However, the situation may be a symbiotic exchange between technologies where progress in one Powertrain benefits the other and vice versa, which is different from the parasitic relationship between the ICEV and AFV observed in the initial appearance of the AFV.

A transition would result in an inter and intra-power-train competition between the incumbent ICEV and newer alternatives. The inter Powertrain competition would produce the new dominant Powertrain. However, competing AFVs are still in development of a dominant design, hence, are in a race to become the most preferred substitute Powertrain to the ICEV. This is subject to the market scale of each technology, which competes for the global vehicle population potential. In addition, Human behavior and choice would always be the most significant issue as the basis of choice of Powertrain has been more linked to the economic and social attributes of the consumer and perceived technological superiority and attractiveness of one Powertrain over the other. Hence, the amount of disposable income per capita, consumer awareness, and education greatly affect the interplay of competing technologies.

The transport sector transition would result in a shift away from oil to minerals such as lithium, cobalt, graphite, lithium, nickel, rare earths, etc. These minerals are the basis of shift to AFVs, such as battery electric vehicles and/or fuel cell vehicles. Thus, as demand for oil diminishes, the demand for critical minerals would grow. Geopolitics, physical availability of minerals, and other uncertainties, however, may impede the shift to AFVs such as battery electric vehicles. Consequently, policies supporting circular economy is one of the identified solutions to these challenges (Srivastava & Kumar, 2022). Figure 5, demonstrates in a causal loop diagram the inclusion of recycling as a circular economy in the production chain of critical minerals. The CLD indicates demand from battery production, which is influenced by production, and the market scale of AFVs influences the demand for critical minerals. The growth in the market scale and existence of AFVs in the market would also generate EV wastes as the number of decommissioned AFVs grow over time. The presence of decommissioned EVs presents an opportunity for adoption of a circular economy via recycling of batteries, which can be applied to meeting the demand for critical minerals.

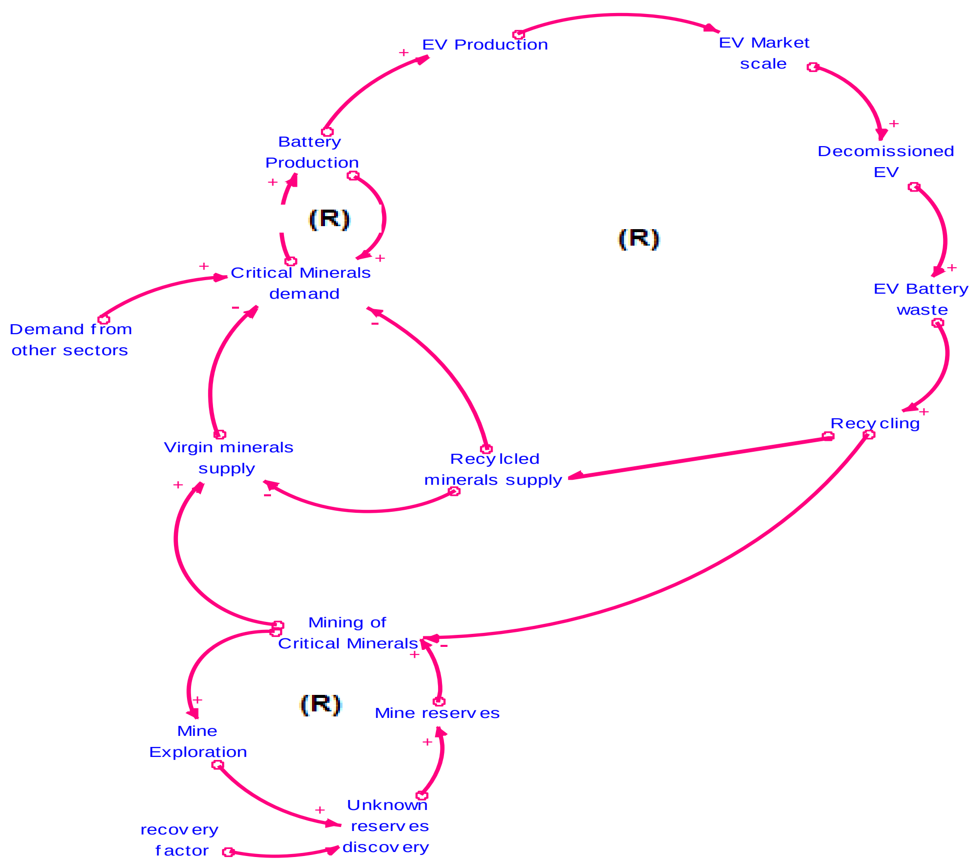

Figure 5: Causal loop diagram for critical minerals

5 Conclusion and future studies

Competition between alternative powertrains has existed since the earliest appearance of alternatives to the horse carriages. However, the nature of their interactions have greatly influenced the dominance or subjugation of one Powertrain over the other. Hence, this study has investigated the interactions between the dominant internal combustion engine, electric vehicle and hydrogen fuel cell vehicles to identify the determining factors from a historical perspective and from diffusion studies. Consequently, a causal loop diagram/framework capturing the most influencing factors has been developed to demonstrate these interactions and direction for future research.

The study identifies several endogenous and exogenous factors influencing the growth of each Powertrain in addition to crosscutting factors influencing the interactions between powertrains. These factors cuts across economic, social and technical factors. The study also identified other cross cutting factors, such as spillover effects and inter-powertrain competition. Although this particular contribution does not quantify the variables identified in the contribution, it is recommended that further research quantify and apply the frameworks

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