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Accelerating the Transition to Alternative Fuel Vehicles through a Distributive Justice Perspective

Abstract

In this paper, we investigate the ongoing endeavor to transition from conventional transportation to more sustainable systems. In addition to the traditional environmental objective, we propose a novel measure to quantify the social performance by using the concepts of Distributive Justice (DJ) and Sustainable Transition (ST) to investigate the adoption of alternative fuel vehicles (AFV). In our context, DJ is defined as fair access to transportation, the latter being a vital means for people to realize their full capabilities in the society. Furthermore, ST measures the social dimension through DJ and the environmental dimension through AFV sales. To model the complex network of relationships characterizing this framework, we use System Dynamics methodology to study the long term impact of considering DJ and ST. Our findings show that policy makers should adjust their targets to consider DJ criteria along with environmental objectives, thus aiming at a sustainable transition. By doing so, they can control and hasten the transition to AFV. Finally, we evaluate the contribution of each policy instrument to guide the policy-making process and catalyze this transition.

Keywords: Distributive Justice, Alternative Fuel Vehicles, Sustainable Transition, System Dynamics.

1. Introduction

The transition from internal combustion engines (ICE) to alternative fuel vehicles (AFV) is becoming an urgent and challenging issue in today's world. According to the International Energy Agency (IEA; 2014), passenger light-duty vehicles account for more than 40% of total transportation energy demand. Also, trillions of dollars will be invested in the near future (until 2035) to increase energy efficiency, with \$2.1 trillion directed toward electric vehicles. If the ICE design remains unchallenged, the carbon dioxide (CO₂) emissions will most likely double by 2050 (Sterman, 2015).

Responding to this circumstance, most major car manufacturers offer a good assortment of AFV, such as the Nissan Leaf and Ford Focus Electric. However, the transition to a more sustainable transportation system is a complex and dynamic process (Zhang et al., 2011; Struben & Sterman, 2008). To date, the history of the AFV transition across nations has exhibited “sizzle and fizzle” behavior, as illustrated in Sterman (2015). Many dominant feedback loops (e.g., transportation networks and infrastructure, research and development (R&D) investments strengthen the ICE dominance and render the AFV transition slow and unsustainable. A key factor in this slow transition is that demand for AFV is strongly influenced by the word-of-mouth (WOM) effect and consumers' willingness to consider such alternatives (Zhang et al., 2011; Struben & Sterman, 2008). Since the latter are both currently

under-investigated and given little attention by policy makers, we aim to investigate the adoption of AFV by focusing on the social dimension of the transition.

Current sustainable transportation objectives established by policy makers solely focus on the environmental and economic impacts of people's current reliance on ICE (Boussauw & Vanoutrive, 2017; Harrison & Shepherd, 2013; Martens et al., 2012; De Giovanni and Esposito Vinzi, 2014a). This approach results in low willingness to consider AFV among potential consumers, as well as in several paradoxes, both leading to an unsustainable transition. Boussauw and Vanoutrive (2017) propose concrete examples of these paradoxes linked to such instruments: 1-Taxing fuel consumption affects more residents of poorer regions, who have longer commutes on average; 2- banning old "dirty" vehicles limits the travel choice freedom of lower income groups that rely on these vehicles; and 3- providing fixed financial incentives penalizes groups with lower incomes because their access to sustainable vehicles is still limited by the high purchase price. These policies aim to incentivize AFV adoption, while being de facto not socially sustainable. Hence, the first contribution of this paper is to explicitly reconsider these policies by incorporating a social dimension, specifically through the Distributive Justice (DJ) concept.

Martens et al. (2012) define DJ in transportation as the indiscriminate and equitable access to transportation, the latter being a vital means for people to realize their full capabilities in the society. The main premise of DJ is that transportation policies should influence travelers to choose environmentally friendly alternatives rather than force them to do so. The DJ principle can help both individuals and governments to fully realize the AFV's benefits.

The development of the DJ index allows us to address the existing trade-offs between the social and environmental objectives of AFV transition previously mentioned in Boussauw and Vanoutrive (2017). DJ implies a lower limit of consumption with maximum policy equity; in contrast, an environmental-oriented policy implies an upper limit of consumption with maximum policy efficiency (Heindl & Kanschik, 2016). Therefore, our second contribution is explicitly analyzing these trade-offs and demonstrating the potential benefits obtainable when policies maximize both pillars. For this purpose, we define an indicator of sustainability that embeds both DJ and environmental objectives, namely, the Sustainable Transition (ST) index that harnesses the potential synergy between the two objectives, thus minimizing the unintended consequences (i.e., worsening of the social objective) and the "policy resistance" behavior typical of complex systems. Because the AFV transition is a complex process filled with many trade-offs, we investigate it by employing systems thinking, particularly system dynamics simulation methodology.

To the best of our knowledge, current research has not quantified the social impact of the AFV transition using the DJ concept. Therefore, we seek to contribute to the literature by developing a DJ index and operationalizing its three components (Equity, Equality, and Need) given our AFV transition context. Using the DJ index, we develop a further index linked to the entire transition process, namely, the ST index. The latter aims at evaluating the system capacity to accelerate the AFV transition through both DJ and environmental principles. We will then use these two indexes to test whether the AFV transition process can be accelerated when policy makers adopt DJ principles in the elaboration of their policies. In particular, we suggest to policy makers how to modify their current policies (e.g., fuel tax, AFV subsidies,

zero emission vehicle (ZEV) regulations) to accelerate AFV adoption when also incorporating DJ principles.

The remainder of the paper is structured as follows. Section 2 introduces the literature on DJ within the framework of AFV transition, highlights the current policy instruments, and introduces our research questions. Section 3 reports the indexes to measure both the DJ and the sustainable transition to AFV. Section 4 introduces the methodology and the model. Section 5 presents the main findings and proposes new prescriptions to policy makers to accelerate the AFV transition process. Section 6 concludes.

2. Literature Review and Research Questions

2.1 Distributive Justice within the AFV transition context

Most of the research on AFV transition focuses on its environmental and economic aspects. Struben and Sterman (2008) develop a systems dynamic model to investigate the transition to AFV and find that subsidies for AFV must remain in place for a long time before the AFV becomes self-sustained. Zhang et al. (2011) design an agent-based model (ABM) to explain the AFV transition. They show that technology push and market pull (such as AFV quota and WOM) both play a positive role in the successful diffusion of AFV. Using an ABM, Eppstein et al. (2011) study the diffusion of plug-in hybrid electric vehicles (PHEVs) and find that the purchase price is the most influential factor in customer adoption. Furthermore, they demonstrate the importance of familiarity with the PHEV technology to its diffusion, even in the presence of financial incentives. Liao et al. (2017) and Al-Alawi and Bradley (2013) compile more than 50 peer-reviewed papers with different methodological approaches sharing the theme of transition to AFV. All these papers focus on the future penetration rate of different AFV alternatives, with no emphasis on the social implications.

While the literature investigates the AFV transition under different perspectives, few papers highlight the social aspects of such a transition (Boussaw & Vanoutrive, 2017; Harrison et al., 2013; Lucas et al., 2012). In particular, the concept of DJ has been disregarded by policy makers in their attempt to accelerate the diffusion of AFV. According to Walzer (1983), goods that have a distinct social meaning should be governed by a “Distributive Justice” sphere to prevent the compounding of inequalities. Martens et al. (2012) define DJ in transportation as the indiscriminate and equitable access to transportation, the latter being a vital means for people to realize their full capabilities in society. DJ’s main premise is that transportation policies should influence travelers to choose environmentally friendly alternatives rather than force them to do so.

In general, DJ consists of three main components (Hulle et al., 2017; Colquitt & Rodell, 2015; Stenman & Konow, 2010) which are explained in more detail in section 3.1: *Equity* (i.e., allocating benefits between different groups proportionally to their respective invested efforts), *Equality* (i.e., allocating benefits between different groups regardless of invested efforts), and *Need* (i.e., providing access to transportation to the maximum number of people). Using these three components, DJ aims to make goods equally accessible and usable for the largest number of individuals. In fact, the concept of DJ adheres to the principle of Pareto optimality, that is, do not leave anyone worse off (Martens et al., 2012; Lucas, 2012).

Although a few qualitative and theoretical studies evoke the use of DJ principles, there are no indicators to explain and measure how a certain policy or a given legislation performs in

terms of DJ. Therefore, the first objective of this study is to develop a DJ index for considering all the aforementioned components (Equity, Equality, and Need), which is called the DJ index. Policy makers can use this index to evaluate and select the best AFV transition policies that uphold the Equity, Equality, and Need principles.

The development of the DJ index allows us to address the existing trade-offs between the social and environmental objectives of AFV transition (see Boussauw and Vanoutrive, 2017). According to Harrison and Shepherd (2013), the current trend of car ownership is not going to change in the near to mid-term future (20-30 years) due to technological and cultural lock-in. Today, people pursue faster and more convenient travel modes, which undermine current efforts toward sustainable mobility (Cohen, 2010). This is known as “car dependence” (Sustainable Development Commission, 2010), implying that car ownership is necessary for full participation in society. Hence, environmental coercive policies (limiting users’ choice set) that may push people into social exclusion are often seen as inequitable. Therefore, we seek to make policy makers aware of the existing trade-offs between environmental and social outcomes and demonstrate the potential benefits when policies simultaneously maximize both pillars. For this purpose, we define an indicator of sustainability that embeds both DJ and environmental objectives, that is, the ST index.

2.2 Research questions

AFV transition entails deep changes to a large socio-technical system (Shafiei et al., 2012; Struben & Sterman, 2008). In such a system, we can assess the importance of the policy instruments in promoting a sustainable transition only within policy portfolios (Edmondson et al., 2018; Bjerkan et al., 2016; Rogge & Reichardt, 2016). Although policy makers’ traditional instruments (e.g., fuel tax, AFV subsidies, ZEV regulations) aimed at optimizing environmental performance work moderately well (Zhang et al., 2011; Eppstein et al., 2011; Liao et al., 2017) , we firmly think that better results can be obtained by also considering DJ targets.

AFV are still in the early adoption phase, so many barriers hinder their widespread diffusion, including battery/vehicle costs, battery range, and lack of charging infrastructure (Bjerkan et al., 2016; Egbue & Long, 2012; Burer, 2009; Diamond, 2009). To pursue our objectives, we focus on the following policy instruments:

- *Fuel tax*: The fuel tax is the most common policy instrument used to collect funds for maintenance of transportation infrastructure and is employed as a deterrent to excessive fuel consumption (Clerides & Zachariadis, 2008). Thus, it has a considerable impact on the AFV transition.
- *AFV subsidies*: Along with the fuel tax, policy makers have introduced subsidies (Wee et al., 2018; Glerum et al., 2014; Qian & Soopramanien, 2011) to mitigate the most critical upfront barrier that consumers face, that is, the purchase price (Brand et al., 2013; Bakker et al., 2013). In the same line, Larson et al. (2014) demonstrate that a direct cut in the AFV purchase price finds significant appreciation among consumers. Therefore, we aim to investigate whether subsidies speed up the adoption of AFV when also considering DJ targets.
- *ZEV regulations*: ZEV regulations are mainly targeted toward manufacturers to incentivize them to introduce low-emission vehicles in their fleets (CARB, 2017; Bjerkan et al., 2016). The government has set a minimum low-emission vehicles quota for cars

sold in the previous three years. The sale of low-emission vehicles generates AFV credits, categorized between those earned by full electric vehicles and those earned by hybrids. If the amount of AFV credits generated is below the minimum quota, an AFV penalty must be paid (CARB, 2017). A certain percentage of this penalty can be reallocated by manufacturers to consumers when purchasing both ICE and AFV. This instrument catalyzes AFV penetration since it actively promotes the manufacturing and adoption of AFV.

Note that greenhouse gases (GHGs) regulation is also part of our model because it is an integral part of current environmental policies (Lee et al., 2010) to drive down emissions. However, *ceteris paribus*, it does not have a noticeable impact on the outcomes from a DJ perspective. This result is compatible with data from the United States Department of Transportation (2017), which show that manufacturers have mostly been able to keep up with the GHG regulations; therefore, GHG penalties are minimal and have no impact in terms of evaluating policies from a DJ perspective.

Most of the policy instruments are based on coercive mechanisms, aiming to decrease the transportation emissions (Harrison & Shepherd, 2013) while fully disregarding DJ principles (De Giovanni and Esposito Vinzi, 2014b). Instead, such policies should be complemented by DJ principles to prevent the disproportional suffering of the economically worse off. According to Boussauw and Vanoutrive (2017), the current policies intensify the tension between the social and environmental objectives. Taxing fuel consumption to affect residents of poorer regions having longer commutes or banning old “dirty” vehicles to limit the travel choice of lower income groups are well-fitting examples. Therefore, we formulate our first research question:

Research question 1. *Can policy makers overcome the trade-offs between environmental and social agendas when catalyzing the AFV transition by adopting DJ criteria along with environmental criteria?*

To answer research question 1, we observe the trade-offs between the environmental (i.e., AFV sales) and social (i.e., DJ index) performance indicators. Then, based on the observed trade-offs, we propose a DJ index to measure the perceived fairness of the AFV transition.

Finally, we seek to suggest to policy makers the best policies (i.e., combination of environmental policy instruments along with their individual strengths) to be undertaken to speed up the adoption of AFV while simultaneously considering the DJ outcome. This implies that decision makers maximize their targets according to the ST index. In particular, we aim to answer the following research questions:

Research question 2. *Which combination of instruments (fuel tax, AFV subsidies, and ZEV regulations) should policy makers use to maximize the ST index?*

Research question 3. *Which instrument (fuel tax, AFV subsidies, or ZEV regulations) provides the highest contribution to the ST index?*

3. Distributive Justice and Sustainable Transition Indexes

For clarity's sake, Figure 1 is a high-level flow chart of the main elements and steps in our methodology, which we will explore in more detail throughout the paper. It illustrates in red our theoretical contributions through the DJ and ST indexes, whose impact we will discuss later in relation to policy makers' decisions.

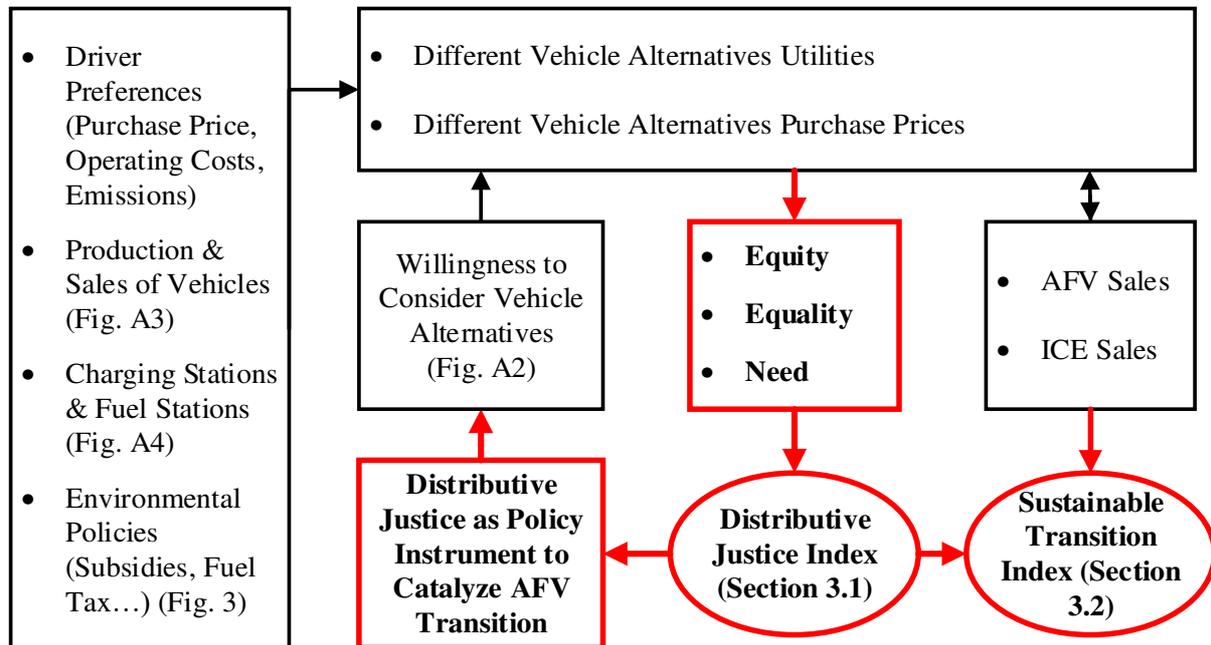


Figure 1: Complex AFV market system investigated through a Distributive Justice lens

3.1 A Distributive Justice index

DJ refers to the perceived fairness of the distribution of social and economic benefits (as well as burdens) among a group of individuals (Stenman & Konow, 2010). Traditionally, DJ has three components (Hulle et al., 2017; Colquitt & Rodell, 2015): *Equity*, *Equality*, and *Need*. To meet the DJ objective, we consider both access to transportation (i.e., Equality of opportunity) as well as the benefit/utility derived from this access to the different vehicle alternatives (i.e., Equality of outcome). Following Hulle et al. (2017), Colquitt and Rodell (2015), Martens et al. (2012), Lucas (2012), and Stenman and Konow (2010), we define:

- *Equity* as allocating benefits between different groups proportionally to their respective invested efforts (the purchase price of a vehicle acts as a proxy indicator of the amount of efforts invested to access and extract utility/benefit from the vehicle).
- *Equality* as allocating benefits equally between different groups regardless of invested efforts.
- *Need* as providing access to transportation (either ICE or AFV) to the maximum number of people.

Each of these components contributes to the final common objective of DJ, that is, fairness in both providing access to transportation and allocating its benefits to consumers. *Equality* refers to “Equality of outcome,” *Need* links to “Equality of opportunity,” and *Equity* is a bridge between the two. Then, we propose operational measures to quantify DJ and its components by tracking the evolution of the purchase price (i.e., input) and utility (i.e., output) of the different alternatives: The former represents the efforts to access the different

types of cars and the latter represents the derived benefit associated with each type of car, which depends, for example, on emissions and running costs.

Following the earlier definition, *Equity* considers the utility of alternatives j , u_j , and their respective purchasing prices, p_j , where j are the different alternatives. We compute the ratios $r_j = \frac{u_j}{p_j}$, which inform us on the benefits derived from the vehicles proportional to the amount of efforts invested to access them. Then, to maximize *Equity*, we seek to minimize the variance in the ratios, $\sigma^2(r_j)$, such that individuals derive the same level of benefit proportionally to their invested effort. So, *Equity* is computed as follows:

$$\text{EQUITY} = \frac{1}{\sigma^2(r_j)}$$

Equality only considers the utility, u_j , of different alternatives by computing the variance in the utilities, $\sigma^2(u_j)$. Then, we maximize *Equality* by minimizing $\sigma^2(u_j)$, such that different groups derive equal benefits from their different vehicle alternatives. Accordingly, we define *Equality* as follows:

$$\text{EQUALITY} = \frac{1}{\sigma^2(u_j)}$$

In the transportation context, the *Need* component is defined as providing access to transportation to the maximum number of people. Purchase price is used as a proxy to access level. The higher the purchase price, the lower the access level. Therefore, *Need* is measured as follows:

$$\text{NEED} = \text{Lowest Access Level} = \frac{1}{\text{Minimum}(p_j)}$$

Finally, we combine all three components into one measure, as follows:

$$\text{Distributive Justice Index} = \sum_{i=1}^3 \text{Weight}_i \left(\frac{\text{Component}_{i,t} - \text{Component}_{i,t_0}}{\text{Component}_{i,t_0}} \right)$$

where $i=Equity, Equality, Need$ and $\sum_{i=1}^3 \text{Weight}_i = 1$. “ $\text{Component}_{i,t}$ ” refers to the level of a component i at time t , whereas “ $\text{Component}_{i,t_0}$ ” refers to its initial level at t_0 . Thus, the ratio shows the relative improvement realized during the analyzed period. In our model, the normalized components vary within the range $[-0.5, 0.5]$, with values higher (lower) than 0 indicating an improvement (worsening) in performance. We split weights equally (i.e., $1/3$) between the three components in accordance with the literature (e.g., De Giovanni & Zaccour, 2014). Nonetheless, we ran sensitivity analyses to check the impact of these weights by varying them between $0.2 \rightarrow 0.4$ while respecting the logical constraint that their sum should always be equal to 1. We notice no qualitative change, meaning that if DJ is increasing (decreasing) with equal weights, it keeps increasing (decreasing) with different weights given to its three components.

If the DJ measure is equal to 0, it is at the same level of the year 2000. If it is increasing above (decreasing below) 0, then it is improving (worsening) relative to its initial level. This indicator allows us to fulfill the first theoretical objective of this research, that is, providing a

measure for DJ that policy makers can use to evaluate whether their actions are aligned with DJ principles (and then, social outcomes).

3.2 Sustainable transition index

To meet the environmental goals, policy makers should lower people's utility from ICE and increase the utility obtainable from AFV, hence increasing AFV sales and reducing the overall emissions. Since there exist several trade-offs and synergies between environmental and DJ objectives, we create a composite indicator that considers both and that we call the *Sustainable Transition* (ST) index. This index allows policy makers to evaluate a given policy (i.e., particular combination of instruments) considering both the DJ index (social performance indicator) and AFV sales (environmental performance indicator) with the target of sustainably catalyzing AFV adoption. The red dotted link between the DJ index and willingness to consider (WTC) AFV in Figure 1 (i.e., link 1→2) is active only when policy makers simultaneously target both DJ and environmental objectives, maximizing the ST index. Such an indicator should consider both the current as well as the transitional dynamics of the DJ index and AFV sales. Specifically, we define the indicator as follows:

$$\text{Sustainable Transition Index} = \sum_{i=1}^2 (\text{Weight}_i * \int_{t=2000}^{t=2035} \text{Impact of Component}_{i,t}),$$

$$\text{Where } \sum_{i=1}^2 \text{Weight}_i = 1$$

The two components are the DJ index and AFV sales. The weights are set by default to 0.5 (i.e., equal importance). Same as with the *DJ index*, we run sensitivity analyses to check the impact of these weights. We notice no qualitative change when we vary its weights. We integrate the impact of each component over the simulation period, thus taking into consideration a negative impact that might occur at any period t . By doing so, we target a smooth improvement of the indicators without relapses. The impact of each component is defined as the difference between its value at period t and the previous period ($t-1$):

$$\text{Impact of Component}_{i,t} = \text{Component}_{i,t} - \text{Component}_{i,(t-1)}$$

The higher the AFV sales and the DJ index, the better the sustainability of the AFV transition. Note that both the DJ index and the AFV sales impact start at a value of 0. For example, if AFV sales are currently 12% (of total vehicle sales), and this figure was at 11% during the last period, then AFV sales have a positive impact of $(0.12-0.11) = 0.01$. If, on the other hand, we have a current DJ index at 0.2, and it was at 0.22 during the last period, then the DJ index has a negative impact of $(0.2-0.22) = -0.02$. So, the larger the increase (decrease), the better (worse) the impact on the ST index.

If the ST index is equal to 0, the AFV transition is at the same sustainability level relative to its initial level at year 2000. If it is higher (lower) than 0, then the AFV transition is more (less) sustainable relative to its initial level at year 2000.

Policy makers can use these indicators when developing policies and instruments to target, among others, social objectives through a DJ perspective. Policy makers can also use these indicators to evaluate the existing trade-offs between environmental and social outcomes and to search for solutions to mitigate them.

4. Methodology and Model

In this section, we present the methodology (section 4.1) and a high level overview of the model (section 4.2) through which we will test the improvements in the AFV transition through a DJ perspective. Then we explore in more details two main parts of the model (sections 4.3 and 4.4) along with the policies (section 4.5), thus introducing all the components needed to measure DJ: The cross-nested logit (CNL) model determines the utilities of the different vehicle alternatives, while the supply-demand dynamics define their purchase prices, with the utilities and purchase prices contributing to the three DJ components. Section 4.6 discusses model calibration and its behavior before introducing different scenarios in section 4.7. See Appendix A for an overview of the model dynamics.

4.1 Methodology

To pursue the objectives of this study, we use System Dynamics (SD) tools, which are hereby implemented through Vensim DSS 6.4. SD is a strategic approach to model and investigate complex systems to better understand the behavior of people, firms and governments in a dynamic setting. Applications of SD cover a wide spectrum, including economic problems (Wunderlich et al., 2014; Forrester, 2004; Oliva et al., 2003; Sterman, 1986), supply chains (Keith et al., 2018; Elmasry and Grobler, 2018; Villa et al., 2015; Saeed, 2009; Croson and Donohue, 2005), sustainable development (Shafiei et al., 2012; Kwon, 2012; Struben & Sterman, 2008; Fiddaman, 2002; Randers, 2000), politics (Cavana et al., 2019; Pruyt and Hwakkel, 2014; Wils et al., 1998; Saeed, 1986), and health care (Paul and Venkateswaran, 2018; Homer et al, 2007; Gonzalez-Busto and Garcia, 1999; Royston et al., 1999). We note that this is the first attempt to implement SD in understanding AFV market and policy implications considering the social dimension through distributive justice and its components.

AFV transition entails deep changes to a large socio-economic-environmental-technical system that is non-linear (e.g., learning), plagued with long delays (e.g., infrastructure installation, production capacity buildup, consumer awareness), and intertwined in a web of feedback loops (e.g., supply/demand/prices of vehicles) (Shafiei et al., 2012; Struben & Sterman, 2008).

Given the complexity of AFV market and its various stakeholders, SD can be considerably effective to capture the most important feedback loops at play in such a transition and investigate the dynamics embedded in a socio-economic-environmental--technical context.

In SD, we measure the most relevant aspects of the problem under investigation (in our case AFV transition) as stocks and flows. A stock Y accumulates changes over time (in our case the timeline is 2000 through 2035), while a flow X is the instantaneous change that increases (or decreases) the stock at each point in time t , resulting in the following dynamics:

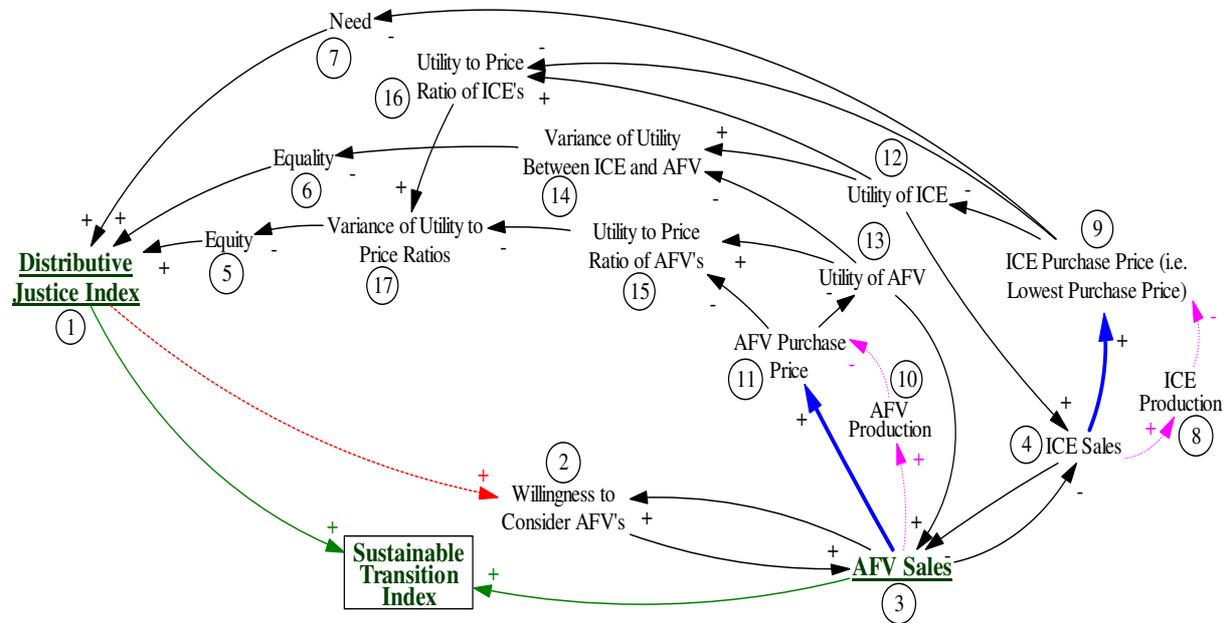
$$Y(t) = Y(t_0) + \int_{t_0}^t X dt$$

For a more detailed introduction of SD, refer to Appendix D, as well as to Barlas (2009) and Sterman (2002). The SD model captures the dynamics behind the transition from traditional to alternative fuel vehicles and its main output is the mix of different types of vehicles between 2000 and 2035. Among the stocks that we consider in our model are: vehicle inventory, purchase prices, emissions, vehicle utilities, willingness to consider vehicles. Furthermore,

among the flows that we take into consideration are: production of vehicles, sales of vehicles, emission rates and R&D investments.

4.2 A system dynamic model of AFV transition

Figure 2 explains the links between environmental (i.e., AFV sales) and DJ targets in a system dynamics model.



Balancing Loops		Reinforcing Loops	
B1	1→2→3→4→9→12→16→17→5→1	R1	1→2→3→4→8→9→12→16→17→5→1
B2	1→2→3→4→9→16→17→5→1	R2	1→2→3→4→8→9→16→17→5→1
B3	1→2→3→11→15→17→5→1	R3	1→2→3→10→11→15→17→5→1
B4	1→2→3→11→13→15→17→5→1	R4	1→2→3→10→11→13→15→17→5→1
B5	1→2→3→4→9→12→14→6→1	R5	1→2→3→4→8→9→12→14→6→1
B6	1→2→3→11→13→14→6→1	R6	1→2→3→10→11→13→14→6→1
B7	1→2→3→4→8→9→7→1	R7	1→2→3→4→9→7→1

Figure 2. Transition to AFV through a Distributive Justice perspective

Note that the + (-) sign at the end of each arrow between its origin A and destination B indicates - ceteris paribus - the sign of the derivative $\frac{dB}{dA}$. To measure *Equity*, *Equality*, and *Need*, we keep track of the utilities and purchase prices of the different vehicle alternatives, which in turn are intertwined in feedback loops with AFV sales and ICE sales. Then, these three components give us the DJ index.

Figure 2 shows 14 loops that connect the DJ index with AFV sales, which are split between balancing and reinforcing loops. When the multiplication of the signs of the arrows along the loop is negative (positive), we identify a balancing (reinforcing) loop. So, if we increase an element in a balancing (reinforcing) loop, we will obtain its relative decrease (further increase).

If we consider the loops passing through the *Equality* and *Equity* components, six of these loops (B1 to B6) pass through the thick blue arrows (i.e., links 3→11 and 4→9). These loops

are balancing and they directly connect the *sales* with the *purchase prices*. The six loops, R1 to R6, passing through the dotted pink arrows (i.e., links $3 \rightarrow 10 \rightarrow 11$ and $4 \rightarrow 8 \rightarrow 9$), that is, the ones that pass through the vehicle production elements, are reinforcing. As for the remaining two loops passing through the *Need* component, it is the other way around (one balancing loop B7 through the wide dotted pink arrow and one reinforcing loop R7 through the thick blue arrow).

We can derive two main intuitions from this. First, the *Equality* and *Equity* components move in harmony with respect to each other, while the *Need* component reflects trade-offs with the other two components. Second, since there are eight balancing loops, we surely have trade-offs between AFV sales and the DJ index. The eight reinforcing loops allow us to overcome these trade-offs, since an increase in AFV sales leads to an increase in the DJ index, which in turn leads to a further increase in AFV sales. However, since three of the reinforcing loops pass through AFV production (R3, R4, and R6), which is limited compared to ICE production, we can suspect that the balancing loops are initially stronger than the reinforcing loops. If the red dotted link ($1 \rightarrow 2$) is activated, the reinforcing loops will grow stronger and eventually overcome the balancing loops, allowing AFV sales and the DJ index to move in harmony. The trade-offs between the DJ components are discussed in Appendix B.

The red dotted link in Figure 2 (link between DJ and AFV sales), seen as a DJ-oriented policy instrument, captures the impact of the perceived fairness of the AFV transition on AFV sales. The DJ index indicates the perceived fairness of such a transition. According to Luo (2007), individuals judge policies and make decisions by considering various justice criteria. Hammar and Jagers (2007) examine the perceived fairness of an increase in the CO₂ tax on gasoline and diesel and report that people show preferences for fairness in policy design by supporting higher CO₂ taxes. Stenman and Konow (2010) confirm that individuals do consider fairness criteria in environmental policies and tend to have a “fairness bias” manifested by judging policies in a self-serving manner. So, people pay attention to policy fairness. Accordingly, we introduce the concept of “fairness bias” into the model, which influences the willingness to consider AFV.

4.3 Consumers’ utility and the vehicle adoption process

There are five types of vehicles in the model depending on their size and fuel-type used: ICE SM (internal combustion engine small to medium-sized vehicle), ICE ML (internal combustion engine medium-sized to large vehicle), H SM (hybrid small to medium-sized vehicle), H ML (hybrid medium-sized to large vehicle), and EV (full battery-powered electric vehicle, no size in this category). These five types are further split between new and used vehicles. For simplicity sake, we bundle the types of vehicles into two main categories: ICE and AFV. We highlight below the most important components of the model.

Figure 2 summarizes the most important elements and dynamics that policy makers consider when investigating the AFV transition process through a DJ lens. In the online Appendix A, we report the main stocks and flows of the SD model in greater detail.

Indeed, the main components of our SD model are AFV sales and ICE sales. These flows are clearly in a trade-off, since increasing the stock of AFV implies a relative decrease in the ICE vehicle stock, and vice versa. Individuals have private motivations for purchasing AFV or ICE (e.g., green/emissions awareness, sensitivity to purchasing price and operating costs,

influence from other drivers). Building on these motivations, the purchasing phase leads to the maximization of individuals' utility, which is estimated using a CNL choice model (Bierlaire, 2006), which takes the following form:

$$\sigma_{i,j} = \frac{\sum_m \alpha_{j,m} x_{i,j}^{1/\mu_m} (\sum_{n=1}^{n_m} \alpha_{n,m} x_{i,n}^{1/\mu_m})^{\mu_m - 1}}{\sum_m (\sum_{n=1}^{n_m} \alpha_{n,m} x_{i,n}^{1/\mu_m})^{\mu_m}}$$

where $\sigma_{i,j}$ is the share of drivers switching from vehicle type i to type j . $x_{i,j} = (W_{i,j} * a_{i,j})$ is the perceived utility of vehicle j by current drivers of vehicle i ; $a_{i,j} = e^{\sum_k \text{indicator}_{k,i,j} * \beta_{k,i,j}}$ is the perceived affinity of vehicle j by current drivers of vehicle i with the k index referring to attribute indicators (e.g., price indicator, emissions indicator). These indicators are formulated such that if they are positive, then the target alternative j is better than the reference alternative i ; $W_{i,j}$ is the willingness to consider vehicle j by current drivers of vehicle i ; $\alpha_{j,m}$ is the degree to which vehicle j belongs to nest m and μ_m is the degree of independence between alternatives within nest m . Within each nest m , there are $n = 1 \rightarrow n_m$ alternatives. If $\alpha_{j,m} = 1$ and $\mu_m = 1 \forall j, m \rightarrow$ CNL model collapses into the standard multinomial logit model. Figure A1 in online Appendix A depicts the choice model.

The vehicle attributes we use in our choice model are purchase price, driving/battery range, emissions, maintenance costs, refueling costs, and availability of fueling/charging stations. We use the CNL formulation since it captures the degree of dependence between relatively similar alternatives (i.e., alternatives that belong to the same nest) while allowing for one alternative to belong to more than one nest simultaneously. For example, an ICE vehicle and a hybrid vehicle belong to the same ICE nest, while the hybrid belongs simultaneously to the ICE and AFV nests. Drivers decide to adopt AFV according to utility maximization principles (CNL model) coupled with bounded rationality; the latter is implemented via a gap between actual and perceived performance and a WTC factor (Struben & Sterman, 2008). The perceived affinity of an alternative is multiplied by its willingness to consider with the purpose of determining its final perceived utility. This WTC factor captures the familiarity of drivers with different alternatives and consequently whether they will consider switching to them. The WTC vehicle j by current drivers of vehicle i at time $t+1$ (i.e., next period) is then:

$$W_{i,j,t+1} = (\rho_{i,j,t} * PF_{i,j,t}) (1 - W_{i,j,t}) - (\theta_{i,j,t} * NF_{i,j,t}) * W_{i,j,t}$$

where $\rho_{i,j,t}$ is the impact of social exposure on the willingness to consider (comprised of marketing effectiveness of a certain alternative and WOM between the drivers of different alternatives), $\theta_{i,j,t}$ is the decay rate of the WTC and $PF_{i,j,t}$ ($NF_{i,j,t}$) are the positive (negative) fairness effect of DJ on consumers WTC AFV. See Appendix A.1.1 for more details about the user preferences and vehicle adoption dynamics.

4.4 Analysis of the production and sales of vehicles

The vehicle stock increases with sales and decreases with aging (in the case of new vehicles) or discards (in the case of used vehicles), as shown below:

$$\frac{dV_j}{dt} (\text{unit of Vehicle/year}) = \text{Sales}_j - \text{Discards}_j$$

The desired sales of vehicle j are determined from the user preferences (section 4.2) plus possible transfer of other alternatives supply shortages/gaps:

$$Desired\ sales_j = \left(\sum_i \sigma_{i,j} (Discards_i + g * V_i) \right) + Gap\ Transfer_j$$

The first half in the equation above is inspired by Struben and Sterman (2008). The " $\sigma_{i,j}$ " is the share of drivers switching from vehicle i to j (it is possible for a driver to decide to keep his or her own type of vehicle). g is the exogenous fractional growth rate meant to replicate the historical demand and its projected forecast through 2035. The gap transfer accounts for the possibility of drivers switching to vehicle j (i.e., their next best available alternative) due to supply shortage of their preferred alternative. This gap transfer is regulated by an algorithm that allocates the different excess of demands (i.e., demand for different types of vehicles that exceed their capacity constraints) to different supplies (i.e., available inventory of different types of vehicles) taking into consideration the preferences of the drivers, the priority of demand sources, as well as the capacity constraints. So, if the preferred alternative of a driver is not available (i.e., shortage of supply), then this driver will be allocated to the next best available alternative (see Appendix A.1.2 for more details). This formulation ensures mass balance in the model, that is, the sum of all outgoing flows is equal to the sum of all incoming flows at all times.

The sales of a particular type of vehicle j are constrained by the available supply of that vehicle:

$$Sales_j = Min (Desired\ sales_j, Supply_j)$$

The supply is determined by the production and sales of vehicles:

$$Supply_j = (P_j - V_j) / Sales\ Period - (P_j\ Outflow - V_j\ Outflow)$$

P_j is the stock of produced vehicles of type j , V_j is the stock of vehicles of type j that are currently being used. This formulation ensures $P_j \geq V_j$. $Supply_j$ is the current inventory of vehicles j that are available to be sold to potential buyers. The stock of new vehicles is determined by the production of new vehicles. Also, in the case of used vehicles, the stock is determined by the aging of the new fleet.

The desired production of vehicles is determined from sales and a reordering point (ROP):

$$Desired\ Production_j = Sales_j + Max((ROP_j - Supply_j) * Demand\ Visibility, 0)$$

The desired production is determined by the new sales plus the existing gap between the ROP and the current supply (i.e., inventory) of vehicles. The gap is only partly observed by the manufacturer since the ROP is determined based on a desired customer service level and desired sales. The production of vehicles is constrained by the production capacity:

$$Production_j = MIN(Production\ Capacity_j, Desired\ Production_j)$$

The change in production capacity (if needed) is determined by the ROP and constrained by a maximum increase of capacity in a year. See Appendix A.1.3 for more details about the dynamics of production and sales of vehicles.

The purchase price of the alternatives is determined based on production and sales:

$$Price_j = \frac{Reference\ Purchase\ Price_j}{Learning\ Multiplier} * \left(\frac{Production_j}{Sales_j} \right)^{Supply\ Price\ Elasticity_j}$$

The purchase price is based on three components: nominal reference price, a learning by doing effect, and the current dynamics of supply and demand.

It is worth noting that the model also considers fuel and charging stations as complementary goods to the AFV technological diffusion. The development of the infrastructure is driven by a desired profitability, which in turn triggers infrastructure investments. See appendix A.2 for more details.

4.5 AFV transition and policy instruments

Figure 3 presents the relationships between AFV and ICE sales with the classical instruments developed by policy makers to accelerate the AFV transition. When policy makers introduce *AFV subsidies*, this intuitively leads to higher AFV sales and, consequently, to lower ICE sales. Higher AFV sales generate larger ZEV credits for the manufacturers, which minimizes the existing credit gaps and credit penalties. Therefore, policy makers can modify the *ZEV sales threshold* to incentivize manufacturers to invest more in AFV development and further increase AFV sales. This policy can have a considerable negative impact on the sale of ICE. Policy makers can use the *fuel tax* instrument to increase these costs even more and further decrease ICE sales, thus favoring the AFV transition. Finally, both AFV and ICE vehicles generate some emissions, whose stock can be regulated through emissions credits. Policy makers directly act on the credit amounts by modifying the *emissions threshold*, thus influencing both the credit gaps and the investments needed to cut these emissions.

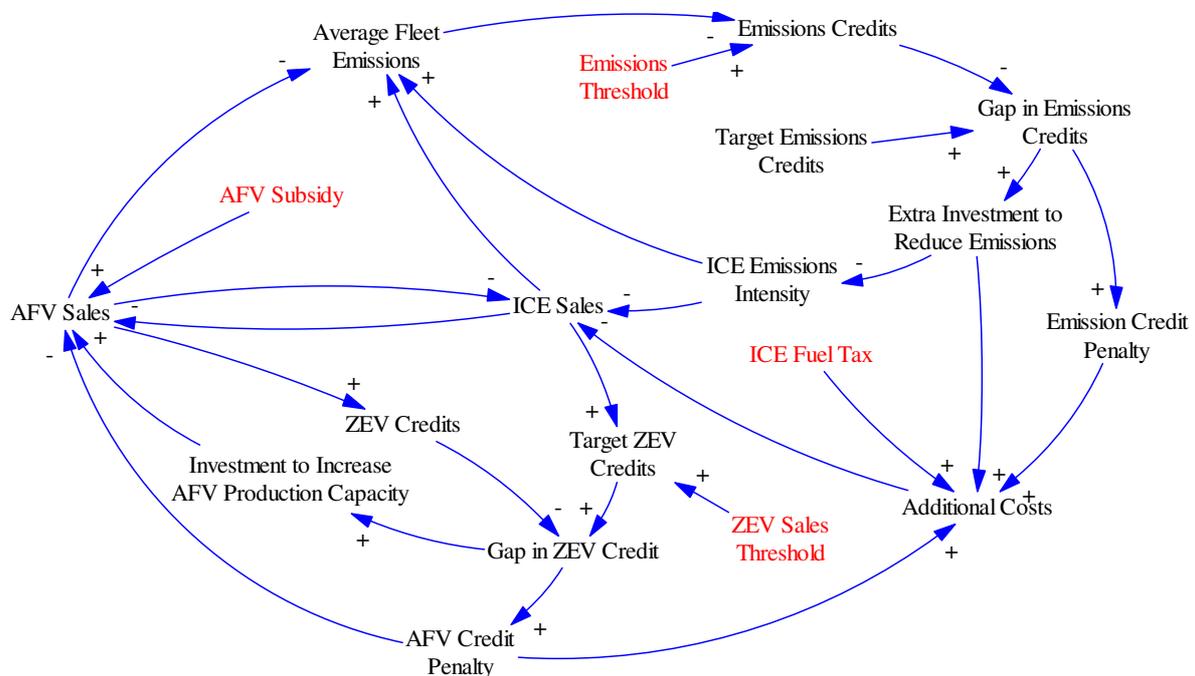


Figure 3. Dynamics of policy instruments

Our baseline scenario is a combination of these instruments at their status-quo levels determined from the literature (CARB, 2017; Walther, 2010). To fill the research gap that we identify in section 2.2 and properly answer research questions 2 and 3, several scenarios are

simulated by varying the parameters of these instruments. This allows us identify the combination of instruments leading to the best balance between environmental performance and social outcomes (see sections 5.2 and 5.3).

4.6 Model calibration and results

As with any model, including SD models, we need to check whether the model can follow the historical behavior observed in real life. If so, we can establish confidence in the model and its ability to provide a good base to judge the policies’ outcome.

We collect historical data (2000-2017) for several key variables in the model, such as sales, vehicle miles traveled (VMT), GHG standards, and ZEV standards (US Department of Energy, 2018a; US Department of Energy, 2018b; US Department of Energy, 2017; US Energy Information Administration, 2017; US Department of Transportation, 2017; US Environmental Protection Agency, 2012). In the case of vehicle sales and VMT, these are secondary data (from reliable governmental sources) since these variables cannot be measured firsthand by definition. In the case of GHG and ZEV standards, these are set by the government and we collect them from public sources. The data are used to calibrate and validate the model behavior.

We achieve a good fit between the model behavior and historical data, as seen in Figure 4. Hence, it is deemed to be representative of reality with its behavior taken as prescriptive of policy outcomes. See Appendix C for more details concerning calibration.

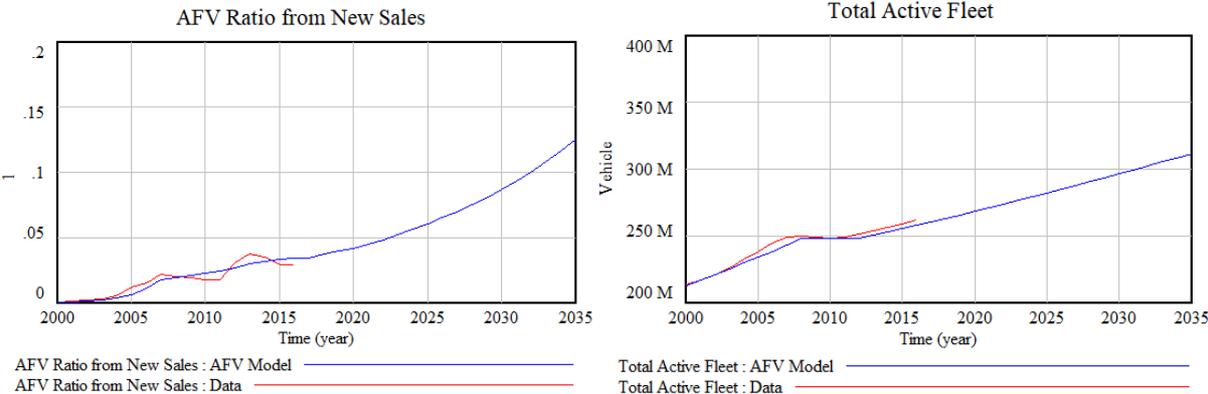


Figure 4: Model vs. data, AFV ratio from new sales and total active fleet of vehicles

In addition, sensitivity analysis tests the importance of the weights assigned to the different components of the DJ index and ST index. Figure 5 shows that the ST index is marginally sensitive to these weights both quantitatively (i.e., value of index does not vary much) and qualitatively (i.e., if index is increasing or decreasing, it does not change directions when we vary the weights).

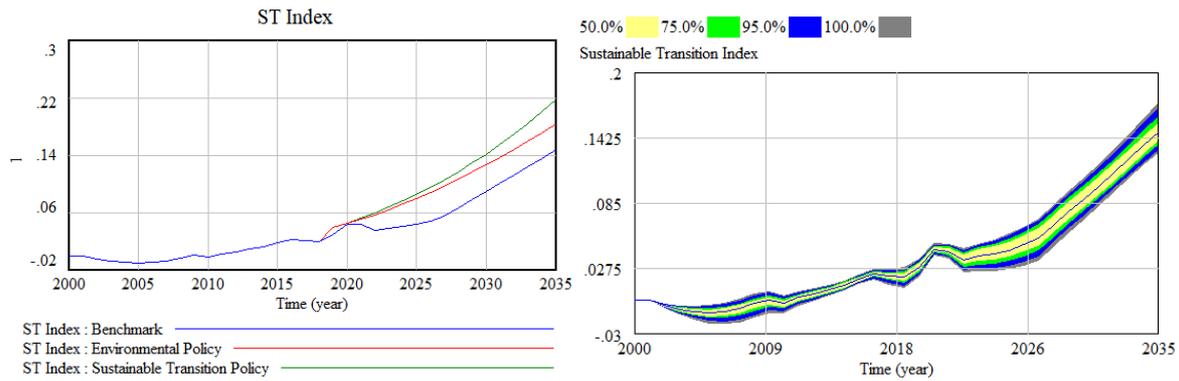


Figure 5: Sustainable transition index behavior under different scenarios (left) and its sensitivity to its two components (AFV sales and DJ index) weights (right)

To test the model assumptions, we run robustness and multivariate sensitivity analysis. Over 3,000 iterations, we simultaneously vary the most important parameters in the model (spanning across sales, production, and policies) within large ranges. Some of the results are shown in Appendix C and demonstrate the robustness of our findings.

4.7 Scenario building

We will use the conceptual model in Figure 2 to investigate the effectiveness of DJ in accelerating the sustainable transition of AFV. To do so, we consider two scenarios:

Scenario 1: Policy makers only consider environmental targets when looking at the AFV transition. We perform the optimization problem by only maximizing the AFV sales with the link between the DJ index and AFV sales being not active.

Scenario 2: Policy makers consider both environmental and social targets when investigating the AFV transition. In this case, we perform the optimization problem by maximizing both AFV sales and DJ, leading to maximization of the ST index. The latter is achieved by activating the link between the DJ index and WTC AFV.

5. Results

5.1 Impact of adopting DJ on policy performance

In this section, we display the results of our research by comparing the outcomes in Scenario 1 and Scenario 2 in Table 1 with the aim of answering research question 1: *Can policy makers overcome the trade-off between environmental and social agendas, hence catalyzing the AFV transition, by adopting DJ criteria along with environmental criteria?*

We target AFV sales (i.e., environmental objective) in Scenario 1 and combine it with the DJ index (i.e., social objective) under the ST index in Scenario 2 in an attempt to overcome the trade-offs. **Our developments in Sections 3.1 and 3.2 provide a new key for reading the transition to AFV and contribute to the theoretical development of this study. In fact, two major contributions drive our results: the development of DJ and ST indexes as well as their long term investigation through SD.** We report a *benchmark* outcome where policy makers set policies (i.e., combination and strength of policy instruments) without having any specific objective in mind. Therefore, Table 1 displays the outcomes of the performance indicators when optimizing with respect to specific objectives. For example, policy makers

can achieve a DJ index=0.33 when optimizing according to the ST index. Accordingly, we derive the following intuitions:

1. The decision maker gets higher AFV sales, which implies a faster transition from ICE vehicles to AFV, by adopting an environmental policy compared to the benchmark scenario ($\Delta=+6.3\%$). Nevertheless, it experiences a decrease in DJ ($\Delta=-6.7\%$) from 0.201 to 0.188. This result informs on the adding value of the DJ and ST indexes. **In fact, disregarding the DJ leaves a trade-off between environmental and social performance that policy makers can only solve when using both DJ and ST indexes during their decision making process. Furthermore, our findings show the trade-offs entailed by policies aiming at environmental performance only and warn decision makers about the need to adopt a more comprehensive policy that also includes social aspects.** Since ST incorporates both DJ and AFV sales targets, the overall performance generated by environmental policy does not improve the social welfare, as it can be perceived as unjust.
2. Decision makers considering DJ principles (Scenario 2) when designing their policies experience an even faster transition process from ICE vehicles to AFV ($\Delta=16.1\%$ compared to 6.3%), and they manage to increase the DJ index as well from 0.201 to 0.334 ($\Delta=65.8\%$). Hence, including DJ principles in the decision-making process allows policy makers to improve DJ as well as AFV sales, leading to a better overall ST index. ST policy is both environmentally and socially sustainable and mitigates all inconvenient trade-offs emerging when using an environmental policy. **This result corroborates our opinion regarding the needs for policy makers to improve their policies by adopting more proper criteria. The DJ index that we propose in Section 3.1 along with the ST index that we propose in Section 3.2 consider the urgent trade-offs emerging in the transition from ICE to AFV and become primary tools in future policy development.**
3. Under the ST policy, individuals perceive the policies to consider the existing heterogeneity among consumers' utility and accessibility to transportation, as well as the differences in purchasing price and benefits of alternative vehicles. Such a policy, as intended by incorporating the DJ index, is seen as fairer. **We seek to highlight that those results are fully driven by the DJ and ST indexes, along with their long term analysis that we conducted through the SD methodology.**
4. If policy makers explicitly convey to consumers (through marketing and awareness campaigns) that they are increasing the fairness of the AFV transition by explicitly adopting DJ principles, the willingness to consider AFV increases as well. In turn, this results in increasing AFV market penetration as seen under the ST policy.
5. Decision makers aiming to accelerate the adoption of AFV should embed DJ policy criteria into their decision-making process. Therefore, policy makers should use both DJ and environmental criteria when evaluating and implementing policies to accelerate the AFV transition because the potential improvements to both objectives can be significantly high. **Moreover, they should definitely consider social dimensions in their decision making process, exemplified by both the DJ and the ST indexes that we propose in this research. Finally, we would mention that the social outcomes are achieved only**

in the long term as they require a deep change in the society’s behavior. Therefore, the social dimension should be analyzed by the use of appropriate dynamic techniques like SD to properly measure the policy impact.

		Range of Instruments	Benchmark	Env Policy (Scenario 1)		ST Policy (Scenario 2)	
				Value	% Change	Value	% Change
Performance Indicators	DJ Index	N/A	0.2011	0.1876	-6.7%	0.3335	+65.8%
	AFV Sales		0.1219	0.1296	+6.3%	0.1416	+16.1%
	ST Index		0.1482	N/A		0.2181	+47.1%
Policy Instruments	Fuel Tax	0→0.2	0.1	0.2			
	Hybrid Subsidy	0→5000	2000	5000			
	EV Subsidy	0→7500	3000	7500			
	Penalty for ZEV Gap per Credit	1000→7500	4250	7500		1000	
	Manufacturer % Transferring ZEV Penalty	0→1	0.5	1		0	

Table 1: Performance indicators and policy instruments under different scenarios

5.2 Combination of policy instruments under different policy objectives

In this section, we answer research question 2: *Which combination of instruments (fuel tax, AFV subsidies, and ZEV regulations) should policy makers use to maximize the ST index (i.e., both AFV sales and the DJ index)?*

Table 1 (bottom rows labeled policy instruments) reports the best values to be used under each policy, which shows that the best combination depends on the policy makers’ targets. The column “Range” informs of the minimum and maximum values that a certain policy instrument can take. Accordingly, we have the following recommendations:

1. When policy makers formulate a policy, the fuel tax should be fixed at the maximum level, independent of the criteria adopted. This policy has negative implications for consumers, who pay more when consuming fuel and show a lower willingness to prefer ICE over AFV. Imposing a policy through penalties threatens the number of ICE vehicles and reduces, consequently, the emissions. At the same time, consumers can intuitively appreciate the mechanism behind it and better realize the benefits in comparison to alternative solutions. Also, they perceive the purchase price difference between ICE and AFV as justified by the high savings eventually linked to the fuel tax.
2. Decision makers should use “penalty for ZEV gap per credit” very parsimoniously and depending on the fixed target. When policy makers consider only environmental criteria, the penalty should be set at the highest level. When DJ criteria are a part of the decision-making process, the penalty should be fixed at the minimum. The latter case also applies when ST is considered, highlighting the idea that DJ is more important than sole environmental criteria to speed up the adoption of AFV.

3. The hybrid subsidy amount and EV subsidy supply a clear and pure incentive for consumers to shift their preferences from ICE to AFV and thus accelerate the adoption process. Policy makers can fix this incentive at the maximum level to simultaneously maximize both objectives. These subsidies make AFV more accessible and affordable, directly acting on the purchase price and increasing the appreciation of related benefits.
4. When manufacturers do not fulfill their obligations and are subject to penalties, the latter should be evaluated by the policy makers according to the targets. When optimizing the environmental policy, the penalties should be fully transferred to consumers, allocating more penalty quotas to ICE vehicles. This will encourage consumers to purchase more green cars and accelerate the adoption of AFV. In contrast, when the optimization problem also includes DJ criteria, manufacturers should not transfer the penalties to consumers at all. Rather, manufacturers should be fully responsible for these penalties and make this information clear to society. Therefore, consumers would appreciate these efforts, feel more responsible in their purchasing decisions, and thus accelerate the adoption of AFV.

When policy makers aim only at reducing emissions, the best policies to be implemented include a maximum fuel tax, maximum ZEV penalty per credit gap, maximum hybrid and ZEV subsidies, and full transfer of the ZEV penalty. In contrast, when policy makers seek to optimize both the environmental performance and the DJ index, the best policies to be implemented include a maximum fuel tax, maximum hybrid and ZEV subsidies, and minimum ZEV gap per credit. Consequently, there is no transfer of the ZEV penalty. **The latter combination naturally depends on the targets that we have in mind with this research, that is, make policy makers aware of the importance of the social dimensions and their measure through DJ and ST. Disregarding these measures directly translate in unjust policies that leave social discrimination and frictions. We would also highlight the requirement of a dynamic and long term analysis. Only the evaluation of long term impacts allows one to appreciate the benefits of the social dimensions.**

We notice that the optimal policy under the ST objective still relies on some coercive mechanisms (fuel tax) as well as potentially paradoxical instruments (AFV subsidies) (Boussauw & Vanoutrive, 2017). This is justified because the current trend of car ownership is not going to change in the near future; hence, coercive policies are needed to bring down the transportation emissions and prevent the deterioration in quality of life to society as a whole due to pollution (Harrison & Shepherd, 2013). However, where possible, such policies should be constrained by DJ principles to prevent the disproportional suffering of the worse off. Such constraints include maximizing access to transportation (i.e., preventing a large increase in ICE purchase prices) and ensuring that different people derive the same utility/benefit from different vehicles, which in our case is realized by minimizing the ZEV-related penalties.

5.3 Analysis of the instruments' marginal contributions to AFV adoption

Here we answer research question 3: *Which instrument (fuel tax, AFV subsidies, or ZEV regulations) provides the highest contribution to the ST index?*

While in Table 1 we display the optimal combination of sustainable policies by acting on each of them simultaneously, we refine this analysis in Table 2. Here, we aim to discover the marginal impact of each policy instrument on the DJ, environment, and ST targets to suggest which policy instruments are to be given more weight in the policy-making process. Table 2 reports the marginal changes in the performance scores when taking the minimum and the maximum of each policy instrument. We compute the benchmarks as the scores obtained by taking the mean of minimum and maximum values of each policy instrument. For example, we take fuel tax=0.1 when computing the benchmark. This allows us to compare the changes in the outcomes to the benchmark. The information that we provide below allows policy makers to select policies to be implemented when some constraints exist. Accordingly, we can formulate the following recommendations, which directly answer our research question 3:

1. We notice that under the environmental policy (status quo) all policy instruments play a positive role in increasing AFV sales, which is their intended goal.
2. ZEV penalty instruments have a conflicting impact under environmental vs. ST policies. They are beneficial under environmental policy (i.e., they increase AFV sales) and harmful under ST policy. In fact, under ST policy, they decrease both the AFV sales and the DJ index because our theoretical foundation considers people’s utility as primary objective in the transition to AFV.
3. When policy makers only target the optimization of environmental targets, they should be aware of the considerable impact of the EV subsidy amount, which provides the higher marginal contributions to AFV sales and environmental performance. More generally, decision makers should use the following classification of sustainable policies to perform environmental targets: (1) EV subsidy, (2) fuel tax, (3) hybrid subsidy, (4) manufacturer percentage transferring ZEV penalty to consumers, and (5) penalty for ZEV gap per credit. This order allows policy makers to accelerate the AFV adoption process when only considering environmental criteria.
4. When policy makers target the optimization of both DJ and environmental criteria (i.e., ST policy), they should focus their effort on the manufacturer percentage transferring ZEV penalty to consumers, which supplies the highest contribution to the ST index. The following classification applies when looking for the optimization of ST: (1) manufacturer percentage transferring ZEV penalty to consumers, (2) penalty for ZEV gap per credit, (3) hybrid subsidy, (4) EV subsidy, and (5) fuel tax. **We note the opposite classification with respect to point 3. This is mainly due to the structure of the DJ and ST indexes, which allow policy makers to focus on social, economic and environmental outcomes. Our DJ and ST developments supply new tools to realize a better connection between the society’s objectives, the environmental targets and the economic outcomes. Therefore, we expect them to play an important role in the future development of sustainable policies with long term impact on the society.**

	Env Policy (Scenario 1)	Sustainable Transition Policy (Scenario 2)		
Instrument Value	AFV Sales	AFV Sales	DJ Index	ST Index

Fuel Tax	0	0.1221	0.1303	0.2442	0.1699
	0.2	0.1236 (2)	0.1322	0.2511	0.1728 (5)
Penalty for ZEV Gap per Credit	1000	0.1227	0.1351	0.2891	0.1941 (2)
	7500	0.1231 (5)	0.1286	0.2178	0.1549
Hybrid Subsidy Amount	0	0.1224	0.1299	0.2316	0.1634
	5000	0.1234 (3)	0.1328	0.2681	0.1811 (3)
EV Subsidy Amount	0	0.1189	0.1269	0.2375	0.1656
	7500	0.1272 (1)	0.1362	0.2587	0.1797 (4)
Manufacturer Percentage Transferring ZEV Penalty to Consumers	0	0.1226	0.1364	0.3005	0.2011 (1)
	1	0.1232 (4)	0.1278	0.2118	0.1513

Table 2. Marginal contribution of policy instruments under different objectives

6. Conclusions

This paper introduces the concept of DJ in the context of AFV adoption and checks its impact on policy makers' sustainable policies and instruments. After operationalizing the DJ concept according to Equity, Equality, and Need, we embed this new concept in a stylized system dynamics model of AFV adoption. We investigate whether considering DJ targets along with environmental targets accelerates the adoption of AFV during the period 2018-2035, as the same path during 2000-2017 evolved quite smoothly. **We use a SD methodology because of the complex network of relationships linked to the AFV transition. Our results are fully driven by two major theoretical contributions: the development of DJ and ST indexes as well as their long term analysis through SD.**

Although the traditional instruments used by policy makers (fuel tax, AFV subsidies, and ZEV regulations) aiming to optimize environmental performance work moderately well, better results can be obtained in the future by also considering DJ targets. In particular, policy makers should look at the sustainable transition index, which includes both environmental and DJ components. By doing so, they can enjoy an increase in the speed of AFV adoption as well as a significant increase in DJ performance. Furthermore, our findings show that DJ provides a large contribution to the adoption of AFV, suggesting that policy makers should abandon the view of simple environmental preservation to also embrace DJ principles.

We look at a combination of policy instruments to optimize sustainable transition targets and accelerate the AFV adoption. We discover that policy makers can speed up the adoption of AFV when a fuel tax as well as hybrid and EV subsidies are set at the maximum level while both the ZEV penalty per credit gap and manufacturer percentage transferring ZEV penalty should be fixed at the minimum level. Our findings suggest that when policy makers adopt instruments that maximize DJ, people are more willing to adopt AFV. This entails an additional operative instrument (complementing the environmental instruments), linked to increasing the perceived fairness of the AFV transition through development of the "willingness to consider" concept, which in turn leads to an increase in AFV adoption.

Finally, we investigate the marginal contribution of each instrument on AFV adoption to provide suggestions to policy makers when some constraints exist (e.g., budget constraints). We discover that when policy makers focus on maximizing environmental targets, they should devote more efforts to the EV subsidy, while investing more on manufacturer percentage transferring ZEV penalty to consumers when maximizing the DJ and sustainable transition targets. We also show that policy makers should prioritize differently the instruments according to the targets they have in mind.

Our results are not free of limitations, which we mention here to inspire future research on this subject. The different vehicle alternatives are summarized under a limited number of types based on fuel type and vehicle size. This simplifies the choice drivers make in real life, but without losing any insights. We focus on the main policy instruments that span the spectrum presented in the literature (Bjerkan et al., 2016); however, there are more instruments to be investigated, including, for example, parking permit fees and road tax/tolling. Another interesting endeavor to test the importance of DJ is investigating R&D investments while considering DJ targets. **The use of SD can leave some drawbacks that can be overcome through the use of other methodologies. The construction of SD models requires very detailed information to draw a big picture of a problem. The collection of all information can be very time consuming while policy makers should often take decisions under time pressure. The use of traditional time-dependent regression models can complement SD in these cases. SD requires that decision makers have long term vision and that the outcomes will be most likely realized in the future. Nevertheless, a long planning horizon analysis can contrast with other objectives that are realized in shorter time periods, e.g., profits. Optimization tools can be used to analyze the problems in short time periods and get a feeling on the future potential of some policies.**

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