Development of Decision Making tool for Sustainable Technologies transition in Indian Transport Sector

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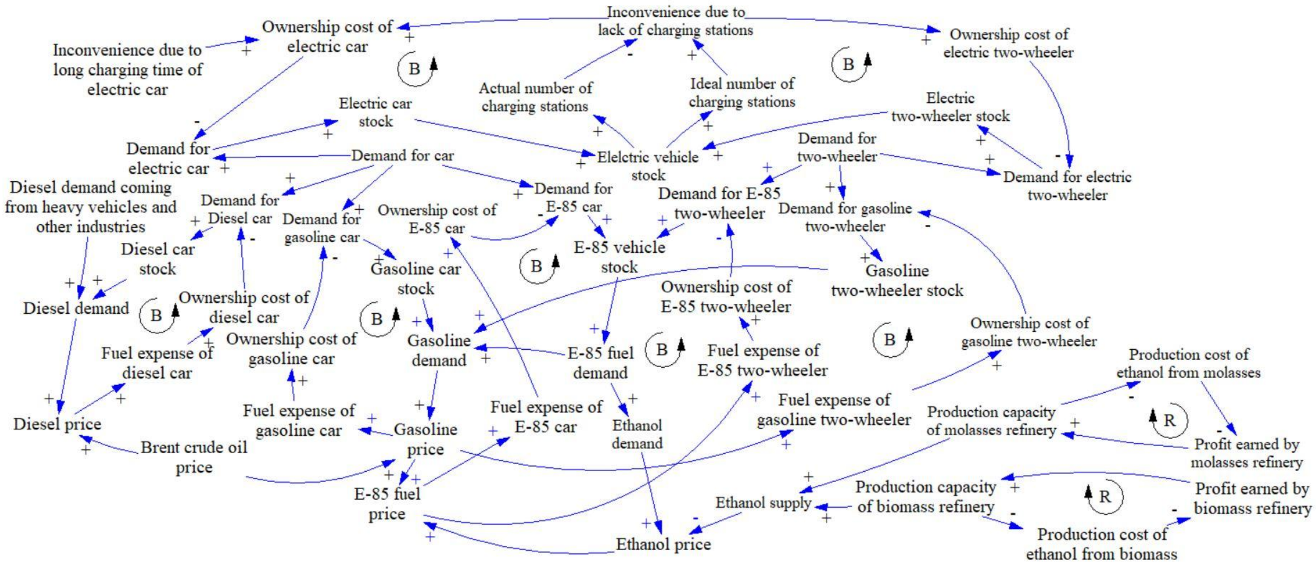
Motivation: India is the third-largest greenhouse gas (GHG) emitting country in the world, with over 132 Mt CO_2e emitted in 2019 (Joshi and Chen, 2020). Under Paris Agreement, the Nationally Determined Contributions (NDC) of India aimed to reduce the emission intensity by 33-35% by 2030 compared to its 2005 level (Joshi and Chen, 2020). Sustainable and green transportation is the key focus area to achieve this ambition. The transport sector is the third largest polluting sector in India, emitting about 45% of country's total GHG emissions (Timperley, 2019). Out of various modes of transportation, the road transport sector contributes to about 73-80% of emissions by entire transport sector (Singh et al., 2019). Growing population and economic development is expected to increase the private vehicle ownership, thereby increasing the total emission. Therefore, transition to low carbon transport options is essential. There have been studies to understand the transition to EVs and biofuels in Indian transport sector using an ANSWER MARKEL model (Shukla et al., 2014; Dhar and Shukla, 2015). It is an optimization model which integrates the environmental and economic factors while aspects like technological and infrastructural dynamics, public acceptance etc have not been considered. Capturing these aspects as dynamics of transport sector would create a likely real-world model to predict the adoption trend of various vehicle options in transport sector. This work has addressed these research gaps in analyzing the adoption trend of E-85 and EVs in private road transport sector in India. System dynamics (SD) methodology has been chosen to accomplish this objective as it takes into account the causal relations and feedback loops to predict the dynamic behavior of the system.

Model Development: The SD model developed in this work focuses on the private transport vehicles in India which includes cars and two-wheelers. The model considers four options for cars, namely, petrol (gasoline), diesel, E-85 and, electric, and three options for two-wheelers, namely, petrol, E-85, and electric. The demand for cars and two-wheeler are the inputs to the model, which are divided among various vehicle options such as petrol, diesel, E-85, and electric vehicles. The annual purchase of vehicle is decided by annual ownership cost of each vehicle option. Annual vehicle purchase gives the respective vehicle stock, which determines the respective fuel demand. Interaction of fuel demand and supply determines the fuel prices, which affects the fuel expenses of the vehicles. Fuel expense increases the ownership cost of the vehicle, which decides the demand of the vehicle for next time step. The key outputs of the model are the annual demands/stocks of various vehicles, price trends for selected fuels, and GHG emissions from private transport sector. Following are the key assumptions used for developing the SD model:

1. Ownership cost is the only factor governing the purchase decision of various vehicle options.
2. Fuel prices, such as, petrol, diesel, and ethanol depend on the fuel supply and demand dynamics.



Model inputs: The model requires annual demand for cars and two-wheelers as well as distance travelled by these vehicles as an input. The national population and GDP per capita govern the vehicle ownership as well as the travel demand. From annual car and two-wheeler ownership, as well as the typical life of a vehicle, the annual demand for cars and two-wheelers is calculated. The correlation of vehicle ownership and travel demand with GDP per capita can be represented through the Gompertz function (Dargay and Gately, 1997).

Vehicle option selection: Once the total annual demand for cars and two-wheelers is known, the demand is divided among the various options based on their annual ownership costs. Other personal factors in decision making are ignored in this version. The multinominal logit model (MNLM) has been used in literature to compares various attributes of different vehicle options and comes up with purchase probabilities (Lin and Greene, 2010). Here, we have used annual ownership cost as the governing factor. Ownership cost of vehicle is the sum of annualised vehicle purchase price, annual fuel expense and, annual maintenance cost. Among these, vehicle purchase price and annual maintenance cost are inputs to the model. In contrast, fuel expenses depend on the fuel price, and therefore, are subject to supply-demand dynamics.

Petrol and diesel prices: The market equilibrium theory proposed by Walras states that the relative change in price of any commodity is decided by the relative change in supply-demand dynamics of the commodity. This has been applied here to calculate change in petrol and diesel prices as function of change in Brent crude oil price and fuel demand. The price change information, along with fuel prices in the previous time step, is used to calculate the fuel prices for a particular time step.

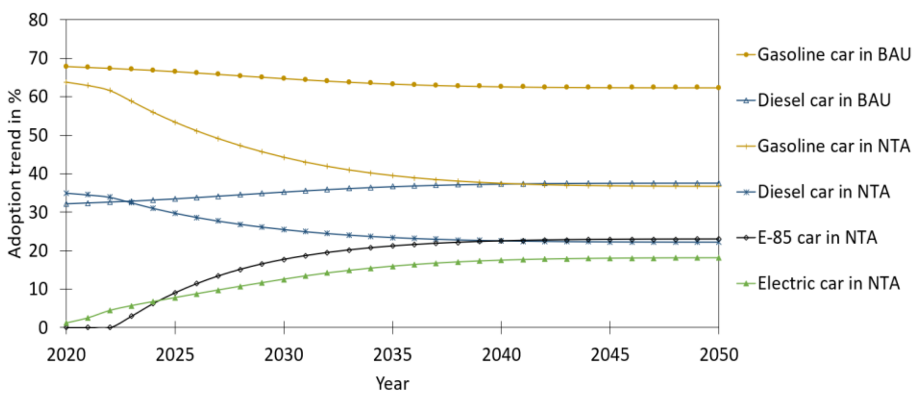
Ethanol supply-demand dynamics: Ethanol for fuel will be produced from molasses, sugarcane juice, and lignocellulosic biomass in biorefineries. The total production of ethanol is positively influenced by the profit earned by the biorefineries. There is a time-lag in the impact of profit/loss on the actual change in the ethanol production which is captured using Autoregressive exogenous (ARX) model. If the total ethanol production is higher/lower than ethanol demand, surplus/shortage of ethanol negatively influences the ethanol price. In case of surplus availability, if the price goes below the production cost of ethanol, the biorefineries incur loss and eventually, reduce the production capacity.

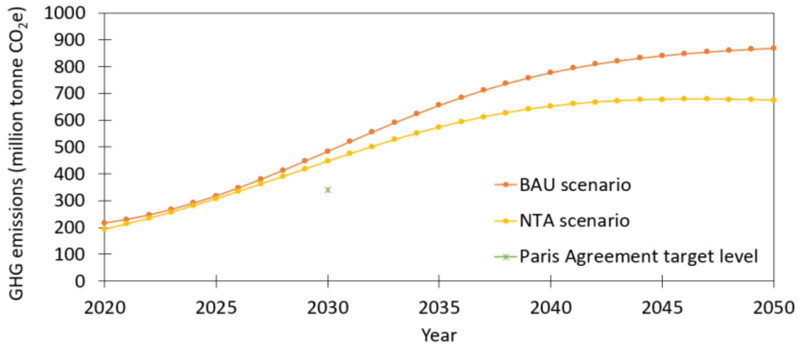
Inconveniences associated with EVs: Apart from high vehicle and battery costs, EV is an inconvenient option due to lack of charging infrastructure and long charging hours. The model converts the inconvenience due these factors into monetary values and adds those to the total cost of ownership of EVs. The inconvenience due to lack of charging infrastructure is calculated by comparing the existing number of charging infrastructure with the ideal requirement as per the EV stock. Also, it has been assumed that as charging technology improves, the charging time will reduce, thereby reducing the ideal requirement of charging infrastructure.

The model was programmed in MATLAB ®. The simulation horizon spanning from 2020 to 2050 and the simulation time step was one year. The model has been used to simulate two different scenarios. The first scenario, termed as Business-as-usual (BAU), assumed no adoption of the novel transport technologies. The second scenario is termed as the New Technology Adoption (NTA) scenario. This scenario assumed the adoption of E-85 vehicles and EVs in the private vehicle stock along with 10% ethanol blending in petrol.

Results for Business-as-usual scenario: Simulation results showed that out of two options available in car, petrol car always had the higher preference over diesel due to lower ownership cost. The petrol and diesel demand increased rapidly with increasing vehicle stock, and the prices increased significantly. The predicted petrol and diesel prices in 2050 were 15.77 $/gal and 17.3 $/gal, respectively. The total petrol and diesel consumption by private vehicle stock in 2050 was 270.6 billion litres, out of which 140 billion litres were consumed by car stock and rest by two-wheeler stock. The GHG emissions from private vehicle stock in 2050 were 869.5 million tonnes CO_2e, out of which 444.6 million tonnes CO_2e, was from car stock, and the rest was from two-wheeler stock. As per Paris Agreement target level, GHG emissions from private vehicle stock should be 334 million tonnes CO_2e in 2030, which is 31% lower than the value found in this study.

Results for New technology adoption scenario: Simulation results showed that petrol driven vehicle was the most preferred option in both car and two-wheeler. However, there was a significant reduction in petrol vehicle stock due to adoption of E-85 and EVs. Petrol, E-85, EVs, and diesel vehicle share in total vehicle stock by 2050 are 60.5%, 21.7%, 9.63% and 8.17%, respectively. The petrol and diesel demand by vehicle stock was 170 billion litres in 2050, which is 37.2% less than in BAU scenario. As fuel consumption reduced due to E-85 and EV adoption, it reduced the expected fuel prices compared to BAU scenario. Petrol and diesel prices were found to





be 11 $/gal and 16.2 $/gal, respectively. Adoption of E-85 and EV reduced the total GHG emission from private vehicle stock in 2050 to 675 million tonnes CO_2e. The share of emission by petrol, diesel, E-85, and electric vehicle stock in 2050 was 56.9%, 19.3%, 17.7%, and 6.1%, respectively. The GHG emission from private vehicle stock in 2030 was 447 million tonnes CO2e, which was 25.3% higher than the target value.

Conclusion: System dynamics model was developed to understand the adoption of E-85 and EVs in private road transport sector in India. Model has considered the dynamics of technological improvement, development of charging infrastructure, and fuel supply and demand in selection of various vehicle options. Simulation result showed that adoption of E-85 and EVs was 31.4% of private vehicle stock by 2050. Significant reduction in fuel demand and consequently fuel prices were observed due to adoption of E-85 and EVs. Although GHG emissions were reduced due to adoption of E-85 and EVs, it was still not enough to meet the India's INDC target level as part of Paris Agreement. As market dynamics was not sufficient to drive the adoption, purchase incentives options for E-85 and EVs are required to be explored.

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