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APPENDIX 4

PROSPECTS AND STRATEGIES FOR ELECTRIC VEHICLES

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Global trends

Road transport currently produces 15-16% of global CO_2 emissions (IEA, 2020a). However, this share is rising rapidly.

Transport uses over 56% of the world's oil production (IEA, 2020b), after transformation into transport fuels (particularly gasoline and diesel), and 40% for road transport alone (Bloomberg NEF, 2020). The traditional view among policymakers and analysts is that the decarbonisation of transport, particularly through electrification, including the adoption of electric vehicles (EVs)1 is a necessary but expensive measure[2]. This may be about to change as a result of falling battery price.

Due to the cumulative effect of vehicle efficiency regulations and EV support policies already introduced around the world, the number of electric vehicles (EVs) on roads have dramatically increased, particularly over the last five years. At the same time, costs have rapidly declined. Battery cost is one of the most important factors in the EV production costs, and thus any decline in battery costs is quickly reflected by lower vehicle production costs. Battery prices have indeed fallen significantly in the past ten years, from US$1,100/kWh in 2010 to US$137/kwh in 2020 (Bloomberg NEF, 2021), largely a result of economies of scale in production and innovation through various forms of learning, as production and sales increase.

Although EV purchase prices at present are higher than for petrol and diesel vehicles, EVs are easier and cheaper to maintain and operate. This combination means that EVs are soon likely to become the cheaper option in lifecycle costs (i.e. once purchase, fuel and maintenance costs are considered together), leading to a likely social 'tipping point' (Sharpe and Lenton, 2021).[3]

However, issues such as high upfront costs, low values placed on future fuel savings, a lack of electric charging infrastructure and range anxiety (McCollum et al., 2017) have impeded programmes. In many European countries economic incentives such as taxes on fuel have had limited impact on establishing a market for EVs[4] or inducing manufacturers to make them available. Fuel duties in Europe and Japan equate to much higher carbon prices than applied to the power sector; in the UK, the duty of £0.58/L of petrol translates to a carbon price-equivalent tax of £252/ tCO_2[5], yet EV adoption in the UK has, until recently, been extremely limited[6].

Taxing existing vehicles and their use does little to help overcome the issues raised above – real or perceived – nor does it necessarily induce manufacturers to improve the availability of EVs. A strategy of simply 'correcting market failures' (particularly market externalities, such as unpriced CO_2 emissions) with pricing instruments to bring to market a new, low-carbon alternative is therefore demonstrably inadequate. However, where a market is already established, adjusting economic incentives through pricing instruments may have greater impact, as illustrated by development of the EV market in Norway ((ICCT, 2018), (Norsk elbiforening, 2020)).

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[1] EVs have much lower lifecycle emissions than petrol or diesel cars, therefore a transition to EVs represents important progress towards reducing global emissions (Knobloch et al., 2020).

[2] This case study focuses on the transition from internal combustion engine to electric vehicles in the passenger transport sector. While we recognize that electric vehicles are likely to be one part of the solution to decarbonizing the transport sector, alongside modal shifts and alternatively-fueled vehicles in other transport sectors, we limit our focus for simplicity and illustrative purposes (ICCT, 2018).

[3] A tipping point towards EVs could arise if a combination of low costs, visibility and positive social reinforcement effects synergise to accelerate a rapid and widespread consumer adoption of the technology.

[4] Tax policies for various European countries are reviewed in ICCT 2018.

[5] One litre of gasoline produces around 2.3 $kgCO_2$.

[6] Until 2018, sales of EVs (excluding hybrids) was below 1%, however in 2019 this climbed to 1.6%, and reached 6.6% in 2020 (Department for Transport, 2021).

Assessing dynamics of a transition to electric vehicles

Decarbonising transport, by any means, is not straightforward, as the sector interacts with a number of other systems and aspects of people's everyday lives. Transition to electric vehicle requires major structural change to overcome incumbent systems. Oil-based transport is at the heart of most activities in the economy and explains why developments in oil markets have historically been strongly intertwined with those in the global economy and geopolitics. The transition to a transport system based on electricity rather than oil will bring with it far-reaching changes to economies across the world, particularly in those dependent on oil extraction, but also to, for example, those that hold – or might hold – substantial sectors in vehicle and component manufacturing. Such a structural shift in transport energy use will therefore influence jobs, imports and exports, and the very structure of the economy (Mercure et al., 2021). Thus, the boundaries of transition processes are very wide.

Various, often opposing influences act within and upon the system to influence the transport choices available, and the choices made. These influences and their interactions can either help accelerate the transition, or work to slow or halt it. Such influences and interactions include:

- Internal combustion engine cars (ICEs) have been subject to vast economies of scale and continual refinement through R&D and other various forms of learning for decades, producing stable vehicle prices (or with increasing performance or functionality). The number of EVs sold remains very small by comparison, and they currently remain at a structural disadvantage. However, the costs of new technologies can decline very rapidly with increasing sales and continued R&D. Some EV models are already competitive in many circumstances when comparing lifetime costs (with low running costs offsetting high upfront costs, relative to ICEs). The advantage is set to continue to move rapidly in favour of EVs, as sales grow and innovation continues (IEA, 2018).

- A key challenge to the widespread adoption of EVs, even where the economics are favourable, is the provision of suitable charging infrastructure. Adoption is held back by a lack of infrastructure, while new infrastructure requires justification from expected use - a 'chicken and egg' coordination problem. Other factors include range anxiety, and general scepticism towards an unfamiliar technology (McCollum et al., 2018). Paradoxically, such issues can be well addressed, directly and indirectly, through widespread EV adoption (McShane et al., 2012; Pettifor et al., 2017) – another 'chicken and egg' problem.

- A widespread shift to EVs would radically reduce demand for, and consequently jobs in, oil extraction, transformation and transportation, the once-dominant petrochemical sector, as well as manufacturing for intermediate products (Mercure et al., 2021, 2018b). Geographies with significant employment in these sectors could form a substantial front of resistance. However, the incumbent vehicle and oil industries have also for decades deployed marked efforts aimed at discouraging the transition to alternative technologies, notably through lobbying and disinformation (Franta, 2021).

- Efforts to encourage the widespread adoption of EVs is occurring in tandem with the development of self-driving intelligent vehicles and other smart features, along with plummeting costs in renewable energy and the development of 'smart' electricity markets and systems, which may reduce electricity prices and incentivise the use of home electricity storage technologies, including EV batteries. Such developments reinforce the attractiveness of EVs over ICEs in the medium term.

The role of different types of policy

The diffusion of new technologies typically follows 'S-shaped' curves, where the initial uptake by early adopters is relatively slow, followed by a more rapid, exponential diffusion with an early majority, before slowing down again when only few late adopters remain (Pettifor et al., 2017; Rogers, 2010). The pace at which a technology moves through this process, and the extent to which is comes to dominate the market, can be strongly influenced by the policy framework within which it takes place.

As discussed above, although classical policy approaches to 'correcting market failures' (particularly internalising unpriced externalities) through instruments such as carbon pricing can have a substantial influence once a new technology is already well established and widely available, they tend not to drive the processes that produce these conditions in the first firstplace (Fevang et al., 2021; ICCT, 2018; Lilliestam et al., 2021). Corresponding to the nature of third domain characteristics[7], various other instruments led by strategic investment are needed and available to encourage a shift from ICEs to EVs (see Figure 9, p. 35 of the main report).

As cost of EV is one of the most important factors for consumers, tax benefits and purchase subsidies have played a significant role in promoting the growth of the EV market. In particular, there is evidence that the purchase subsidy policy for EV has stimulated adoption for price-sensitive consumers (Lévay et al., 2017; Lu et al., 2022). EVs have also been made more attractive to consumers by generous tax benefits in Norway, leading to rapid EV penetration in that country. However, the purchase subsidies also bring increased financial burdens to the public sector (Lu et al., 2022) and the tax incentive schemes can result in revenue losses (Holtsmark and Skonhoft, 2014).

Fuel and CO_2 efficiency regulations have been used around the world for many years, and although they have led ICEs to become more efficient, they have so far not encouraged the adoption of alternatives (ICCT, 2021a). This is perhaps in part a function of stringency; they may well induce greater change if their requirements exceed the limits of what may be achieved by ICE vehicles. Limited evidence exists on the effectiveness of ICE vehicle phase-out policies, such as those announced in the UK and EU, although in principle these regulations incentivise the industry to supply the market with alternatives, with competition driving innovation and cost reductions, in anticipation.

However, this remains to be seen (ICCT, 2021b). Conversely, EV mandates directly address the issue of alternative supply by placing requirements on manufacturers to sell a certain number of EVs as a proportion of their total sales. By requiring the sales of EVs, alongside simply making them available, such mandates can induce positive feedbacks including EV cost reduction, demand for charging infrastructure, and social familiarity. They are likely to be the most powerful individual policy instrument for driving the adoption of EVs, as seen through their use in California (Wang, 2020), British Colombia, Quebec (Sykes and Axsen, 2017) and China (Wang et al., 2019).

A number of existing studies (Axsen et al., 2020; Bhardwaj et al., 2020; Lam and Mercure, 2021) find that well-designed combinations of the above instruments can lead to a greater rate of transition than may be achieved through the application of any individual instrument, by addressing different elements of the problem – including supply of the new technology, facilitating infrastructure, and shaping user preferences and choices.

[7] Third Domain economics is concerned with the pace and the type of the many processes that enhance productivity, intensity and choice of different resource uses over time (see (Grubb et al., 2015, 2014)).

Modelling the transition

Figure 1, top row, shows projected costs of EVs in China, India and Brazil under different learning rates , if recent deployment rates continue ('Baseline'). Various forms of learning accrue from expanding global EV production and R&D. The horizontal black lines represent the median vehicle price (solid) and lifetime cost of owning a mid-range petrol vehicle (dashed), while the three declining dashed lines show different plausible trajectories for the median price and lifetime cost (including electricity use) of owning and operating a mid-range EV. Since ICE vehicles have been refined over decades, with relatively little opportunity for innovation remaining, little to no cost reductions are to be expected, while rapid cost reductions are expected to continue for EVs.

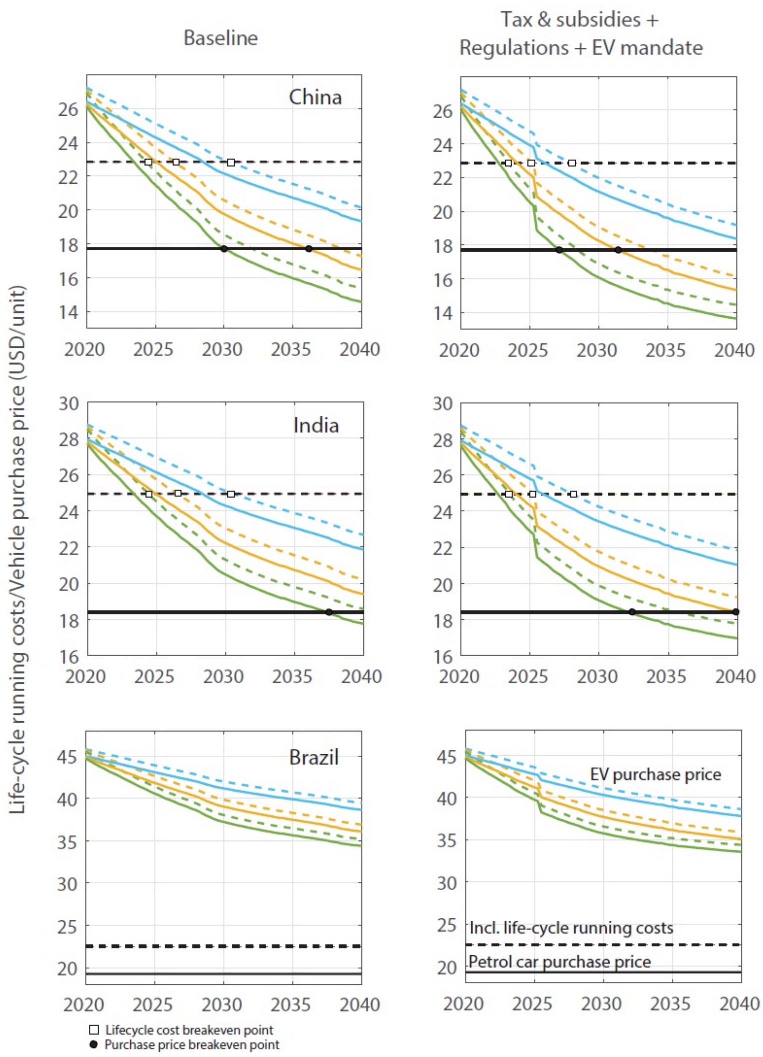

Figure 1: Time at which vehicle cost and price parity can be expected to arise between electric and standard vehicles in China, India and Brazil, in the current trajectory of technology and costs. Country differences arise due to different vehicle model availability, industry mark-ups and policy regimes. Cost parity estimates assume a typical vehicle consumer discount rate of 20%, while price parity estimates do not require any discount rate assumption.

[8] The different curves depend on the accuracy of existing knowledge on the rates of learning and battery costs, which are uncertain. This value expresses the rate of cost reduction for each doubling of cumulative EV production, of which variations leads to different time spans until parity is reached.

The points at which those cost trajectories cross the black dashed line indicate the time at which cost parity could materialise, without additional policy support.[9] Once this point is crossed, it becomes more expensive to own and operate an ICE vehicle. This could produce a 'social tipping point', after which societies begin to permanently move away from ICEs (assuming non-cost barriers, such as EV charging infrastructure, are appropriately addressed) and policy measures, such as subsidy mechanisms, may be drawn down or removed. This could be as early as 2028 in China and likely no later than 2035 in both China and India (at present, very few EV models are available in India). In Brazil, price parity is not achieved if the present conditions are maintained, and the price difference between EVs and a mid-range petrol car is much higher than in China and India. This is due to a general lack of policy for increasing EV deployment in Brazil, the pricing and import tariffs on EVs, and lack of EV model choice.

Using the evidence discussed above, we model the impact of different additional transport decarbonisation policies – individually and in combination – on the potential transition to EVs (and other alternatively fuelled vehicles) in India, China and Brazil (see Figure 12, p. 46 of the main report). We examine the impact of three broad groups of policies: pricing policies (subsidies and taxes), regulations (fuel economy standards and phasing out fossil fuel vehicles) and EV mandates. We find that, on their own, none of these options are sufficient to drive the required shift to EVs by 2050. We even find that combining policies of the same type (e.g. adding subsidies to carbon and fuel taxes) generally leads to worse outcomes (a detailed study is given in (Lam and Mercure, 2021). However, combining policies of different types in many cases leads to strong synergies.

Figure 2 shows the diffusion of EVs if existing policies and other trends continue (the 'baseline' case - first column) and what happens with the sequential addition of other policy instruments (subsequent columns). The baseline projection suggests that EVs and plug-in hybrids (PHEVs) are making real progress in China, although not enough to achieve far-reaching decarbonisation before 2060. However, India remains petrol-dominated for the foreseeable future, while Brazil has become locked into its flex-fuel technology allowing vehicles to use any blend of ethanol and petrol.[10]

[9] Depending on how quickly innovation takes place, and the rate of time preference of consumers. Since the majority of fuel expenditures happen often years after purchasing a vehicle, the lifetime ownership cost comparison requires the inclusion of the rate of time preference, or discount rate, set at 20% here, since consumer discount rates in car markets are typically very high. For the price parity comparison, no discount rate is necessary. For any rate of discounting, fossil fuel costs are in all cases substantially higher than electricity charging costs over a vehicle's lifetime. Lowering the discount rate implies cost parity happening sooner.

[10] Ethanol is a low-carbon alternative to petrol in Brazil, however it is not carbon neutral and has generated long-standing concerns over its sustainability (Fargione et al., 2008; Searchinger et al., 2008).

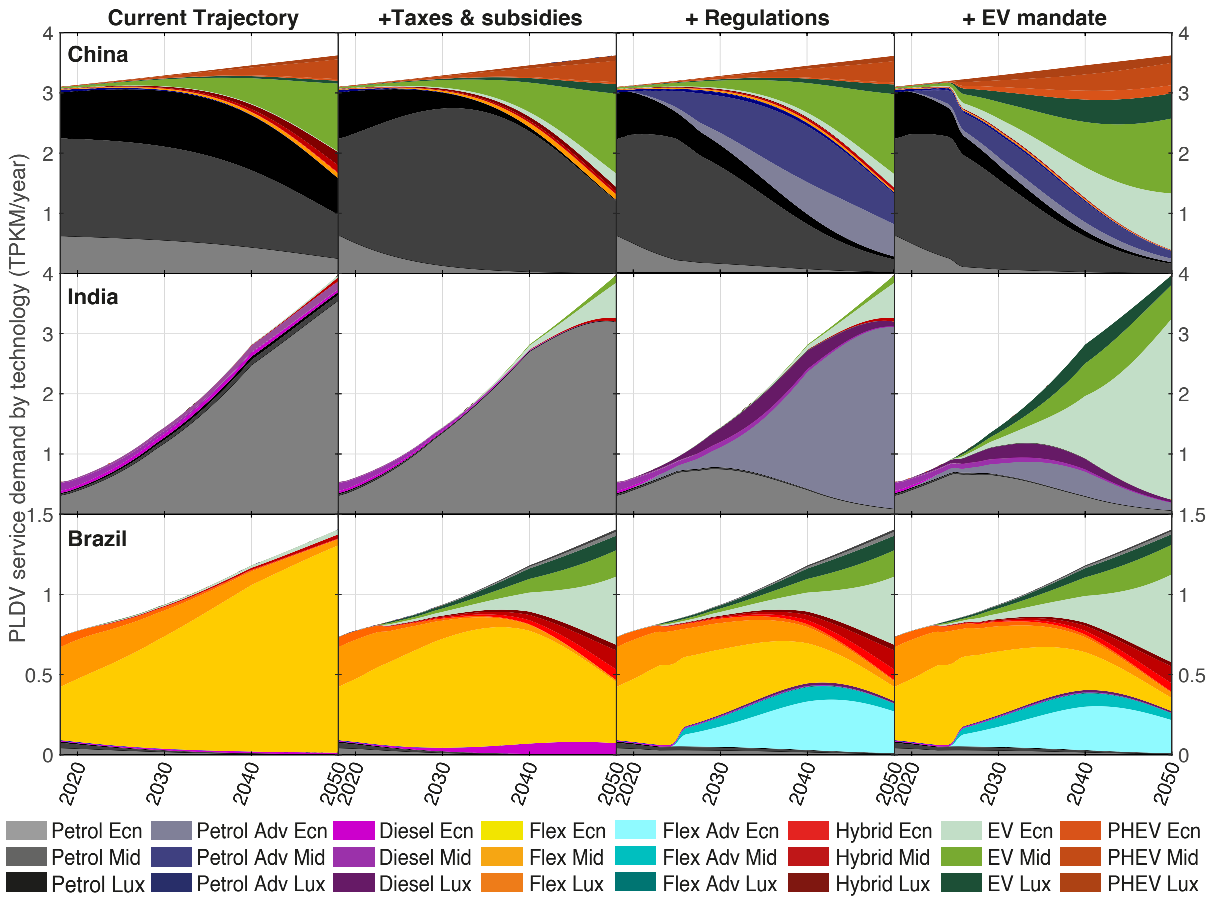

Figure 2: Scenarios of evolution of the technological composition of passenger light duty vehicle (PLDV) fleets in India, China and Brazil up to 2050 under different regimes of policy. The Baseline projects current observed trends. Policy instruments include Road Taxes, Vehicle Taxes, Electric Vehicle Subsidies (together called 'Taxes & Subsidies), fuel economy regulations (Regulations) and EV mandates. Technologies are divided in three classes of engine power: Economic (Econ), mid-range (Mid) and luxury (Lux) and include standard petrol and diesel, a new generation of higher efficiency petrol engines (Petrol Adv), Brazilian Flex-Fuel that can use any mix of ethanol and petrol (Flex), higher efficiency Flex-Fuel (Flex Adv), non-plug-in hybrids (Hybrid), electric (EV) and plug-in hybrid-electric (PHEV).

The introduction of road and vehicle taxes linked to CO_2 emissions and EV subsidies help accelerate the transition, but their effect is limited in all countries (second column). The addition of CO_2 or energy-efficiency regulations can play an important role in eliminating inefficient combustion vehicles (third column). Although the rate of decarbonisation increases with application of these two policies, it is not sufficient. However, the rate of change increases dramatically when EV mandates are added on top of the other policies early on (fourth column). As with the other policies, EV mandates alone cannot achieve the decarbonisation profile illustrated. Thus, the model suggests that the combination of economic incentives, vehicle regulations and EV mandates provides the most suitable policy environment for a rapid transition to EVs to take place (Lam and Mercure, 2021).

The rationale for why this works is simple. Pricing policies are effective at incentivising consumer choices away from more carbon-intensive and less-efficient technologies, but without a wide availability of EVs, there is no outlet towards which to orient those choices. EVs are not yet widely available, nor is the charging infrastructure, and market variety is poor. Many consumers who are unable to choose an EV that would suit them, or even to get an EV at all, might just pay the tax associated with an ICE vehicle. Similarly, for the fuel-efficiency regulation, supplying more combustion vehicles to the market, albeit of higher efficiency, will not achieve decarbonisation if EVs are not widely available. Resolving the supply problem of EVs can be accelerated using the EV mandate and can also be accelerated through various forms of public procurement. Both approaches provide scale to the market. But the mandate may fail if the market policies are not there to ensure a sales volume. Hence, both must happen together.

Going back to Figure 1, it is clear that the policy framework brings down the price of EVs more rapidly in all countries, moving forward the date of purchase price parity with conventional vehicles to achieve lifecycle cost parity before 2030 in both China and India. This suggests that subsidies for EVs would not be needed for much longer. For Brazil, although EV fleet number is on the rise, the transition has been slow compared to China because of import limits and taxation structures that favours the existing ethanol and flex-fuel vehicles industry.

What are the risks?

The primary risk of a rapid electromobility transition is that the industries and systems that support the manufacture and use of ICEs may decline or become redundant at such a pace that a wider transition strategy cannot be formulated and implemented, with resulting impacts on jobs, communities, the value of financial assets and even financial stability (see Mercure et al., 2021, 2018):

- Countries highly reliant on oil exports will be negatively affected, while countries relying on oil imports will see an improvement to their trade balance. However, most countries have domestic petrochemical industries that would suffer declining outputs.
- Jobs in petrochemicals are likely to decline substantially, not necessarily replaced by jobs in the EV sector or supporting industries (including an expanding electricity sector).
- The effect on jobs in vehicle manufacturing will depend on the degree to which individual manufacturers transition towards EVs. However, large numbers of intermediate products in the value chain for ICEs, which have no use in EVs, may become obsolete (Fredriksson et al., 2018).

Since oil, derived fuels, vehicles and vehicle parts are highly traded internationally, these impacts are highly transboundary. For example, a rapid shift to EVs in China could affect jobs in the oil sector in Russia, Canada and the US, and manufacturing in Germany and Japan. This underlines both the value of international cooperation on climate and clean innovation policy, and that a lack of wider domestic action to drive and prepare for such transitions is a risky strategy.

What are the opportunities?

Important direct and indirect opportunities arise with the decarbonisation of transport. Direct opportunities are well known; they involve drastically reduced air pollution, the creation of employment in vehicle manufacturing and the development of high-value supply chains. For the latter, the reality may be more complex than first appears, as it depends on, for example, the competitiveness of the local manufacturing sector, and whether and how many vehicles are imported versus made domestically. The creation of domestic employment can overcome the losses of employment in high-carbon sectors.

However, the indirect opportunities can be much larger. These stem from the process of reducing imports of oil - an important factor for China, India and Brazil. The current oil import bill for these countries exceeds, respectively, US$200bn, US$100bn and US$2bn per year in 2021 (Brazil is an important oil and ethanol producer) and with current trends could rise up to values exceeding US$500bn, US$300bn and US$5bn in 2030 if unabated demand for fuels maintains its growth (OPEC, 2020).

China already has a well-established EV manufacturing value chain, but Brazil and India do not. Whether or not these countries develop domestic or contribute to global EV value chains, the effect of reducing the import bill for oil and oil derivatives can contribute a very important source of additional domestic spending. In practical terms, EV-owning consumers could increase spending on general goods and services, money that would otherwise have been spent on imported liquid fuels. This can have an economic boosting effect across all sectors, particularly in the services.

At approximately the point when EVs are predicted to achieve ownership cost parity with conventional vehicles, whether or not the vehicles are imported, a positive impact on GDP may be felt. The impact could be up to twice as large if EVs are manufactured domestically.[11] Overall, the transition to electric mobility increases economic productivity as it reduces input costs. However, this happens at the expense of oil-exporting countries, as the job losses are offshored there by large importing countries such as India and China (Mercure et al., 2021). In Brazil, the electrification of mobility could result in output declines for the domestic oil and ethanol industries (assuming exports do not increase), which could cause political challenges.

Conclusions

It is clear that limiting policy action to adjusting economic incentives, as would be suggested by the traditional CBA and the theory that underlies it, is inadequate to encourage the rapid and widespread adoption of EVs. Economic incentives alone do not encourage a new technology, and the surrounding systems of infrastructure, supply chains and individual societal preferences and choices, to establish and change. Packages of policies that also address these issues must also be introduced to drive the early stages of transition, before social tipping points are reached that may herald a permanent shift toward the new technology, after which its diffusion accelerates and becomes self-sustaining.

[11] This since, roughly speaking, the value of the lifetime use of fuel for a petrol car is similar to the price of the car itself, while the lifetime use of electricity by an EV is approximately three to five times lower, and electricity is generally domestically generated. For a country that imports both EVs and oil, the oil import bill is saved, while for a country that imports both but begins to make EVs, the import bill saved is twice as large. For a country that makes conventional vehicles and begins importing EVs, the effect on the import bill probably to some degree cancels off.

The Future Technology Transformations Model for transport

The ‘Future Technology Transformations’ (FTT) family of technology models aims at predicting the technology composition of certain chosen sectors that contribute significantly to CO_2 emissions worldwide. The models are based on a similar and comparable time step simulation framework that seeks to reproduce the observed S-shaped diffusion curve of technologies. FTT models exist for power generation (Mercure, 2012; Mercure et al., 2014), road transport (Mercure et al., 2018a; Lam and Mercure, 2021), heat (Knobloch et al., 2019) and steelmaking (Vercoulen et al., 2019). They all involve all major low and high-carbon technologies in use in their respective sectors, together covering 88 technologies.

Here we examine the S-shaped diffusion of car technology in India, China and Brazil using the FTT Transport simulation model, which tracks the availability, adoption and cost reductions in different vehicle markets worldwide. The model simulates observed S-shaped technology diffusion dynamics in which more prevalent vehicle models receive more attention and thus diffuse more easily, while less prevalent models see a long and slow initial diffusion before reaching mass markets, as is known to happen in markets (McShane et al., 2012). The model is parameterised by detailed cost distributions, sales and fleet composition data by technology type and market segment. It includes learning-curve cost-reductions that arise through global scale accumulation.

FTT models assume that each year or quarter, a new tranche of technology units enters the fleet (whether cars, power plants, etc.) and statistically lives for a duration determined by a survival likelihood. The technology composition of the new tranche of units is determined by choices of heterogenous agents. Each agent sees a technology universe of which the composition is determined by the prevalence of technology. For example, technologies in early phases of diffusion are available to very few agents, since their sales, production and the knowledge over their existence are all limited. The more technologies diffuse, the more they become available to agents, in a positive feedback loop. The learning-by-doing curve reinforces this effect, where with growing sales volumes, the costs of new technologies also come down.

The preferences of agents that determine the composition of the yearly new tranche of technology are determined on the basis of pecuniary and non-pecuniary costs organised in a comparative manner. For example, for cars, the model assumes that agents compare options on an equal basis of cost per kilometre travelled, using a consumer discount rate to estimate the relative value payments made in the future against those made in the present (e.g. when they trade off in their decisions fuel costs in the future against capital costs in the present). Agents are thus hypothesised to compare all the vehicle options that they know and choose on the basis of comparisons. Pecuniary costs are those that can be quantified with available data. Non-pecuniary costs correspond to how agents value intangible aspects (e.g. comfort, brands, engine power class), determined on the basis of values that enable the model to match observed diffusion profiles. All costs are treated as distributions assuming that agents are heterogenous populations, and therefore cost comparisons involve comparing distributions.

The result of this model is an ever-changing technology composition, with new units entering the fleets and old units scrapped as costs and preferences evolve. Policy instruments can either influence costs or what can be, or is being, sold. They can accelerate the observed changes or alter the direction of evolution of the model. The model generates projections consistent with recent observations, where for instance the rate of diffusion of EVs at the start of simulations matches what is observed in the most recent year of data.

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