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Revisiting Jevons' Paradox with System Dynamics – Systemic Causes and Potential Cures

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Summary

This paper examines the dynamic relationship between the consumption of goods and services, technological efficiency, and associated resource use, as described by the theory of Jevons' Paradox. A theory is presented about what causes Jevons' Paradox, in which resource efficiency savings are eventually overtaken by increases in consumption to produce a net increase in resource use and therefore Environmental Impacts. An application of the theory was carried out using system dynamics, modeling CO_{2e} emissions from private road transport in the UK between 1970 and 2010. The model results indicate the approximate impact of Jevons' Paradox within the historical period: a rise in travel consumption of about a half and a rise in CO_{2e} emissions of about a third. The model was used to estimate whether the EU goal of a 40% drop in CO_{2e} emissions by 2030 is achievable in the road transport sector, by adding interventions, and the results indicate that higher increases in fleet efficiency than are currently forecast, costlier travel, and a reduction in travel consumption would all be required. The theory and model presented in this paper highlight the need to implement a system of interventions that can influence the strength and direction of each of the feedback loops within the system being intervened with, if CO_{2e} emissions are to be more reliably reduced than they are at present. And because the system is constantly evolving, intervening with it requires a responsive and holistic approach, while maintaining focus on a long-term goal.

Introduction

The need to reduce the Environmental Impacts (EI) of human activities has been firmly established by science, yet EI continue to grow broadly in line with economic activity. One of the most common solutions put forward is to "decouple" resource use, and therefore associated EI, from economic activity through eco-efficiency. Eco-efficiency is a measure of the relationship, within economic activity, between *'environmental cost or value and environmental impact'* (Huppes & Ishikawa 2005), or put more simply the effort towards, *'doing more with less'* (Braungart & McDonough 2009). Holm and Englund (2009) define two types of macroeconomic decoupling: in "relative decoupling" the rate of resource efficiency increase is less than the rate of GDP increase, and so total resource consumption does not fall; in "absolute decoupling" resource efficiency outpaces gains in GDP and so the total amount of resources used decreases. Efforts to achieve absolute decoupling can be undermined by different forms of rebound, a mechanism whereby part, or sometimes all, of the savings in resource use gained through efficiency are "taken back" when users increase their consumption of goods and services. This happens because *'technological improvements evoke behavioral responses'* (Binswanger 2001). At the macroeconomic level, this behavioral response appears as a gap between the expected drop in resource use from eco-efficiency investment and actual resource savings, called the Gross Rebound Effect (Vehmas et al. 2004).

The dynamic relationship between the consumption of goods and services, the lifecycle efficiency of the provision of goods and services, and the EI associated with that provision is complex and currently not fully understood.

Jevons' Paradox

One economics theory related to gross rebound in a capitalist economy is described by Jevons' Paradox (JP), originally from (Jevons 1865) and defined by Saunders as: *'with fixed real energy prices, energy-efficiency gains will increase energy consumption above what it would be without these gains'* ((Saunders 1992) from (Sorrell 2009)). The theory developed by Jevons proposes that, paradoxically, technological efficiency can lead to an associated growth in resource use. Sorrell (2009) finds that JP is more likely to be true for energy efficiency improvements during the early stages of diffusion of general purpose technologies. Hertwich reviewed different types of rebound from an Industrial Ecology (IE) perspective and found that the way rebound is normally defined is not complete enough to account for the secondary effects associated with it, which include *'behavioral and technological spill-over effects, transformational effects, and positive and negative side effects'* (Hertwich 2005).

Historical evidence for JP is difficult to find because it happens over a long time frame and relevant data is not always available; however, there are several studies that provide evidence which is consistent with (but does not prove) the theory. Two examples are: (i) Fouquet and Perason (2006) gathered data on lighting efficiency, technologies, and consumption over several centuries in the UK. Taking data from their study, we find that in the UK, between 1700 and 2000, although lighting technology efficiency (in lumen-hours/kWh) grew by a factor of 925, per capita energy used for lighting (in kWh/person/year) still grew by a factor of 39, due to per capita consumption of lighting (in lumen-hours/year) growing by a factor of 36,600. (ii) Dahmus (2014) reviewed the potential for eco-efficiency to reduce resource consumption over the long term (from 1900 to 1960). For all ten of the technology activities reviewed, over the whole period the rate of increase in the quantity of goods and services provided outstripped the rate of increase in efficiency, resulting in a net increase in resource consumption.

We find few detailed theories about the dynamical causes of JP in the literature. Sorrell finds it likely that there exists a synergistic relationship between economic growth and energy consumption, with '*each causing the other as part of a positive feedback mechanism'* (Sorrell 2009). Ruzzeneti and Basosi (2007) identified the existence of a circular feedback process within which increasing time lags come into play: a quick response (direct rebound), a slow mechanism (indirect rebound), and a long-term restructuring process that affects overall economic structure (general equilibrium effects). Ayres (2002) describes resource consumption as both a driver of growth and a consequence of growth, and represents the growth mechanism as positive feedback cycle between consumer demand, industrial investment, declining unit costs, and lower prices for consumers, as represented in the Salter Cycle Growth Engine.

The work of several authors in studying the relationship between consumption and resource use highlights the need to consider eco-efficiency along with its secondary economic effects, including: (i) Garrity examined JP with the use of Causal Loop Diagramming[i], developing a model of business industrial growth and consumer behavior, described as a *'loop you can't get out of'* (Garrity 2012). (ii) Hilty et al. (2006) modelled the potential impacts of ICT on sustainability with system dynamics, finding that although ICT can make public transport more efficient and lower its CE intensity, there will be a rebound effect that leads to more traffic and possibly more energy consumption. (iii) Fischer-Kowalski et al. (2008) developed a model that can predict freight transport volumes from national material flows, finding a strong correspondence between these two values, and that distances per freight haul have shown a tendency to increase over time. (iv) Cleveland and Ruth (1999) found a lack of compelling evidence that the U.S. economy has decoupled from material inputs, highlighting a lack of understanding about the degree to which aggregate economic growth tends to offset efforts towards dematerialization.

Dynamic Modeling

System Dynamics (SD) is a methodology that can be used to model and simulate socio-technical systems as information feedback control systems, in which the environment affects decisions made by human actors, whose actions, in turn, affect the environment. The modeling process has been described by Luna-Reyes and Andersen (2003) as involving four stages: (i) conceptualization (problem definition and system conceptualization); (ii) formulation (positing a detailed structure and selecting the parameter values); (iii) testing (model behavior and model evaluation); and, (iv) implementation (policy analysis and model use). There are three types of variables in SD models:

- "Stocks" or "levels" in SD represent accumulations either of physical things or of non-physical factors that influence system behavior and change slowly; stock values are calculated with an integration equation that adds the value of flows going into the stock and subtracts the value of flows draining out of them.
- "Rates" or "flows" define the rate at which accumulating or draining processes in the model move things into or out of the stocks; their value is calculated with an equation that takes values from other stocks or auxiliaries as inputs, and can range from a simple arithmetic formula to a more complex differential equation.
- "Auxiliaries" can influence flows but do not directly influence stocks; they can be defined as constants (sometimes used to represent exogenous influences on the system) or as variables, in which case their values are calculated with an equation that takes as inputs values from other stocks or auxiliaries (from (Lane 2008)).

According to Sterman (2000), the behavior of a system arises from its structure – consisting of positive (reinforcing) and negative (balancing) feedback loops, stocks and flows – and nonlinearities created by the interaction of the physical and institutional structure with the decision-making processes of agents acting within it. Reinforcing loops, which cause growth, amplify whatever is happening in the system; balancing loops, which are goal seeking, counteract and oppose change.

Research Steps

Assuming some robustness to the theory of JP, this paper seeks to understand its causal mechanisms and asks if it is always inevitable. For the remainder of this paper we use the term CO_{2e} Emissions (CE) as a proxy metric for the full range of EI; this is because of the wide availability of CE data, because we are principally interested in understanding relational trends rather than absolute amounts, and because CE generally rise and fall in line with EI. There were four steps to the research:

1. Develop a theory about the mechanisms and structures involved in JP.
2. Apply the theory to build a SD model of one example of JP: CE from road transport in the UK between 1970 and 2010, using Vensim[ii] software.
3. Use the model to investigate the size of the JP effect in the historical period, and whether it would have been possible to reduce the effect through interventions.
4. Extend the model out to 2030 to see what interventions would be needed to meet the EU's CE reduction goals.

A Causal Theory for Jevons' Paradox

We develop here a more endogenous causal theory about JP than currently exists, based on several theories from the social sciences and historical evidence. We apply Giddens' structuration theory (1984). Jones and Karsten (2008) describe structuration as a process in which human agents' actions draw on social structures, whilst these actions both produce and reproduce social structure. Applying this theory to JP requires us to first identify the relevant social structures involved, and because JP is a socio-technical phenomenon we must also identify the physical structures involved. There are four key structures at play in JP.

Economic Growth: Capitalist countries have economic growth as an objective, which is enabled by higher resource use, technology development, and efficiency (Ayres 2002). Technological development is endogenous to economic growth; the rate of change of technology is dependent on the rate of capital accumulation in the economy (Bresser-Pereira 2013).

Social Norms: Social norms are highly influential on individuals' behavior. They can be descriptive, specifying *'what is done, based on the observation of the majority of others'* (Darnton 2008) or injunctive, specifying *'what other people think ought to be done'* (ibid.). In this paper we use the term social norms to represent societal expectations about levels of affluence, which is reflected in the average level of consumption per person of goods and services.

End-Use Technology Structures: These are physical and institutional structures related to the widespread use of technologies by end-users and controlled by private organizations, including the supply chains that produce end-use technologies, maintain them, provide the fuel to run them, and (in some cases) process them at end of life. For example, vehicle manufacturers design and mass produce vehicles, garages maintain vehicles, the fuel on which they run is sold through a network of filling stations, and scrap yards break them up at end of life.

Public Structures: These are publically funded structures that support the widespread use of end-use technologies. Support comes in the form of financial incentives, legislation on safety and standards, and (in some cases) the provision or regulation of the physical infrastructure needed for the widespread use of technologies, such as road networks.

How do these four structures co-evolve with agents' actions, through the process of structuration? We describe here our theory about four of the mechanisms involved (there are likely to be more), which interact with the structures.

Commercial Competition: Commercial enterprises grow through selling existing products and services to new customers, or new products to existing customers. Commercial competition leads to technological innovation, which creates new and/or cheaper goods and services. Commercial success reinforces the economic growth structure.

Demand Creation: Marketers stimulate market demand for new products or services, which leads to more use of technology to carry out everyday activities or an increase in the variety of what people do. For example, computer games instead of playing cards for entertainment. Successful demand creation supports the development of end-use technology structures.

Ratcheting: Due to a ratcheting effect, individuals in society get used to and then expect increasing levels of affluence. Shove describes this as a one-directional process, with *'mechanisms of path dependent ratcheting'* ((Shove 2003b) from (Bartiaux et al. 2011)). Ratcheting supports increasing social norms, meaning higher expectations of comfort and technology use.

Government Policy Making: Decision makers in public bodies support economic growth and the widespread use of technologies through activities such as funding R&D and providing a growth-focused regulatory framework. This mechanism supports the development of more public structures.

To summarize the theory, it is not simply that technological efficiency leads to lower costs and so to increased consumption through the workings of the market, the dominant social construct in capitalist society is a belief in continual economic growth and technological efficiency's role is to *enable* this. Similarly, Ayres states that the rebound effect has driven the economic growth that has been seen over the past two hundred years in many countries (Ayres 2002).

Application: Modeling Private Road Transport Emissions

The causal theory was applied to a real world example of JP: private road transport in the UK between 1970 and 2010. During this period there was a decoupling between CE from road transport and GDP of approximately a third – a relative decoupling effect – but an absolute rise in CE/person. Total direct and embodied CE approximately doubled between 1970 and 2007, then between 2007 and 2010 they fell back to 1992 levels, due partly to improvements in vehicle efficiency, recession, and higher fuel prices.

Although road transport vehicles have been well studied within the field of IE, Graedel et. al. find that industrial ecologists have *'overemphasized cars as products and underemphasized the transport system of which the car is such a major part'* (2002).

Physical Stocks	total vehicles in use (vehicles) road network (km of road)
Soft Stocks	social norms on travel and freight (dimensionless) supply chain investment in technology development (dimensionless)
Consumption	vehicle purchases (vehicles/year) non-freight travel per person (vehicle-km/person/year) freight travel per person (freight-km/person/year) road congestion (vehicle-km/km of roads/year)
Technology Efficiency	fleet efficiency for personal vehicles (km/liter) fleet efficiency for freight vehicles (km/liter)
Economics	disposable income (£/person) GDP (£bln) price of vehicles (£/vehicle) retail price of fuel (£/liter) annual cost of road travel per person (GBP/person)
Environmental Impacts	direct CE from freight and non-freight vehicles ($MtCO_{2e}$/year) embodied CE from road building, road maintenance, supply of fuel, and manufacture of vehicles ($MtCO_{2e}$/year)
Exogenous Values	UK population (persons) international fuel market prices (£/liter) non-transport related factors impacting GDP (£bln)
Exogenous Uncertainties	**Political Ideology:** uncertainty about changes in politics that could prioritize either private transport or public and non-motorized transport (dimensionless) **Science and EU Policy:** uncertainty about how science and EU policy will influence the UK's environmental regulation that promotes increasing fleet efficiency (dimensionless) **International fuel markets:** uncertainty about how much fuel prices will vary from current forecasts up to 2030 (dimensionless) **GDP:** uncertainty about changes to the forecasted GDP by non-transport factors (dimensionless)

Table 1: Key concepts from the theory about Jevons' Paradox as represented in the system dynamics model

The observed growth in UK road transport CE up to 2007 was driven in part by the pro-private transport policies of the Conservative government in the 1970s and 1980s. The following Labour government developed a set of policies aimed at reducing traffic growth in the 1990s; however, it failed to achieve the goals of its policies – partly due to succumbing to pressure from private transport lobby groups (Docherty & Shaw 2011). Thus, we include in the model the influence of political ideology, which affects the building of travel infrastructure and support for different public, private and non-motorized modes of transport.

Modeling Approach and Structure

To build the model, we first identified the key factors that cause JP – consumption, technology efficiency, and economics; then identified the physical infrastructure involved; and then identified the balancing and reinforcing feedback loops that our theory says cause the observed system behavior. Table 1 presents key elements of the model and their units. Values for dimensionless variables are only significant in how much they rise or fall in relationship to other variables.

The model is presented in the form of a Causal Loop Diagram, which is a simplified versions of the full SD model. Further details of the model and a complete model diagram are provided in the supporting information. To interpret the diagram, positive causation between elements is represented by black arrows with a "+" sign (δB/δA>0 *ceteris paribus*), while negative causation is represented by grey arrows with a "–" sign (δB/δA<0 *ceteris paribus*). Balancing loops are named B1, B2, etc. and reinforcing loops are named R1, R2, etc. The model is presented in two forms, according to the level of rebound.

The **No Rebound (NR) model** (Figure 1) represents the case where CE/person are reduced (against a baseline of no efficiency improvements) through technological efficiency. Fleet efficiency improvements, driven by higher fuel costs and environmental regulation, reduce the emissions intensity of vehicle-km and freight deliveries. This represents an idealistic technology solution and not historical evidence. Vehicle-km and freight/person will still rise in step with rises in disposable income, according to economic theory, and so CE/person may still rise; however, – there are no *corresponding* changes in consumption due to efficiency gains. The model includes one reinforcing loop and two balancing loops:

(R1) links fleet efficiency to the cost of road travel – as costs are reduced, travel increases, which leads to more supply chain investment.

(B1) limits growth in vehicle-km per person due to the cost of fuel.

(B2) limits growth in vehicle-km per person due to the cost of vehicles.

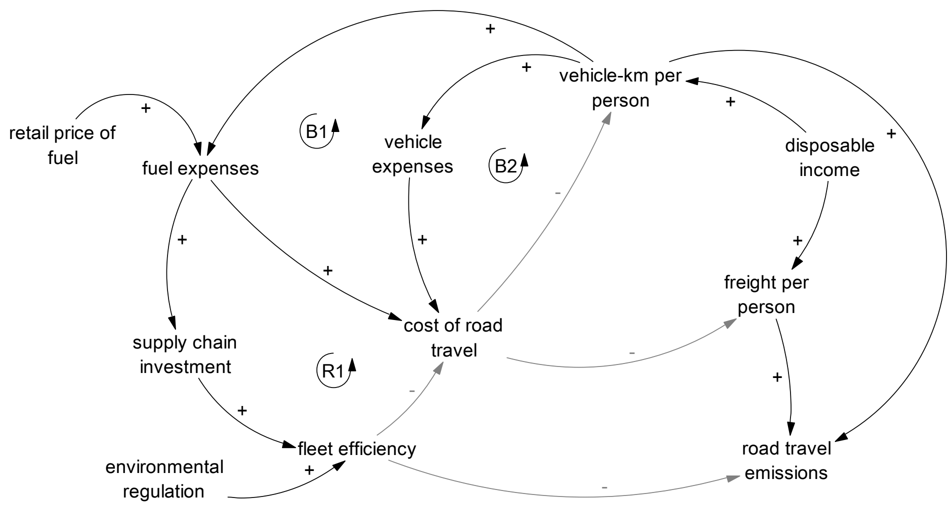

Figure 1: The No Rebound model for UK road transport, in which efficiency gains lead to reduced CE/person (against a baseline of no efficiency improvements), although absolute CE/person may not fall

The **Structural Rebound (SR) model** (Figure 2) represents historical trends from the UK's road transport system and economy, according to our theory about what causes JP; it includes direct and indirect rebound and general equilibrium effects. There are several additional feedback loops, compared to the NR model, which lead to increases in the size of infrastructure and levels of consumption – and therefore in CE/person. There are four uncertainty factors which can affect the growth in consumption and infrastructure, named "uncertainty: ". The additional balancing loops and reinforcing loops are:

(B3) limits growth in vehicle-km due to road congestion.

(B4) leads to road building, which stops when congestion levels have fallen.

(R2) links travel costs to social norms - as people get used to travelling more, the social norm (societal expectations about what a normal level of consumption is) increases, which in turn influences consumption of travel.

(R3) links travel costs to consumption of freight – as people get used to having more goods, the social norm increases, which influences consumption of goods.

(R4) links the size of the vehicle fleet to supply chain investment – as investment increases, vehicle costs decrease due to production efficiency, which then helps to drive further fleet additions.

(R5) links vehicle fleet size to increases in GDP – as travel consumption increases, this influences GDP to increase, leading to increases in disposable income, which leads to growth in travel and freight consumption.

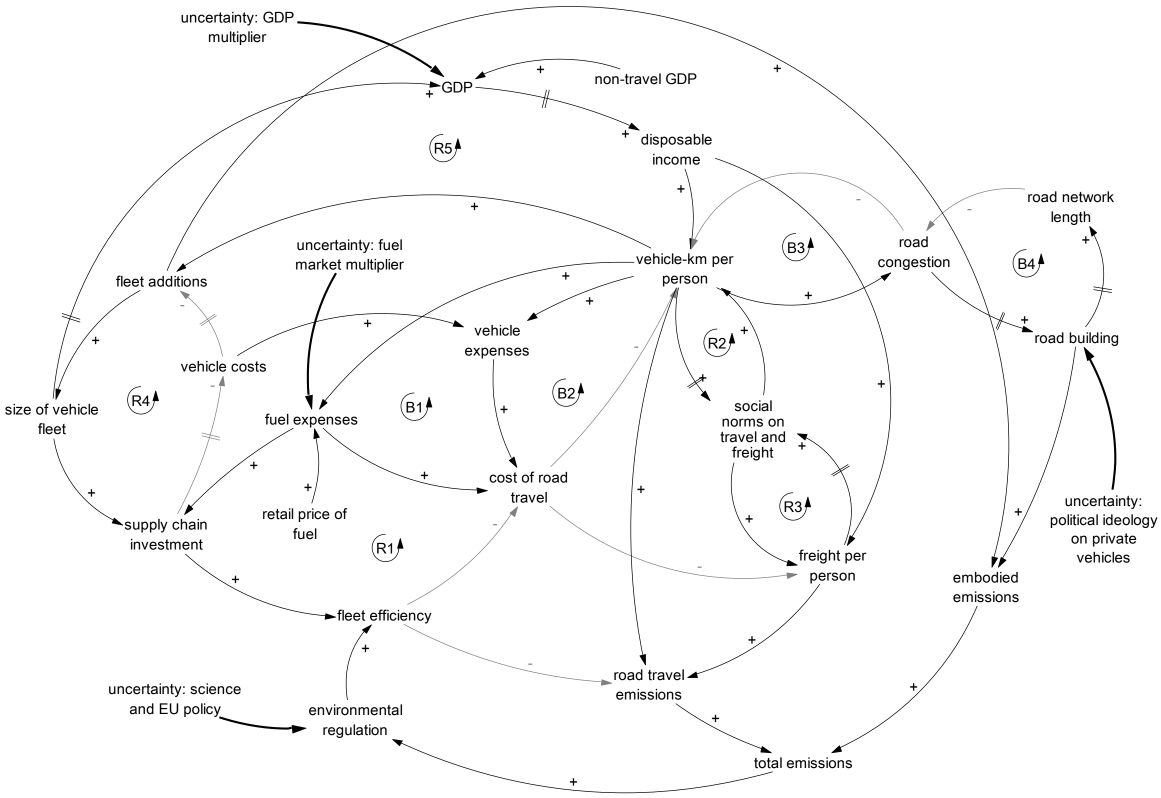

Figure 2: The Structural Rebound model in which efficiency gains lead to increases in social norms, increased consumption of travel and freight, and a growth in infrastructure – all of which cause higher CE/person

Most, but not all of the elements from our causal theory about JP are represented in the road transport model; the model is an example application of the theory, while the theory could apply to any technology type for which JP has occurred. Linking the causal theory and the model structure, the four structures from the theory are represented as follows: economic growth – the link between GDP and size of vehicle fleet; social norms – social norms stock; end-use technology structures – vehicles in use stock; public structures – road network stock. The four mechanisms from the theory are represented as: commercial competition – growth in supply chain leading to reduced vehicle costs and increased efficiency; demand creation – not directly represented in the model as this is a mature technology but implicit in supply chain investment; ratcheting – feedback loop between social norms and consumption rates; government policy making – rate of investment in road building and environmental regulation.

Modeling Results

The SR model was calibrated to historical data (1970 to 2010) and then the NR model was developed as a version of the SR model with the effects of rebound taken out. Details of the data used for the model calibration are provided in the supporting information. Figure 3 shows CE from UK private road transport as direct (from the burning of petrol or diesel) or embodied (from the consumption of energy to build new vehicles and roads, to maintain roads, and to supply fuel). Spikes in model embodied emissions are due to the estimate that road building schemes occur every few years. Accumulated CE is a good indicator of total impact on the environment over the period, while trends in CE per year illustrate how emissions rise or fall in line with other variables such as cost of travel or disposable income.

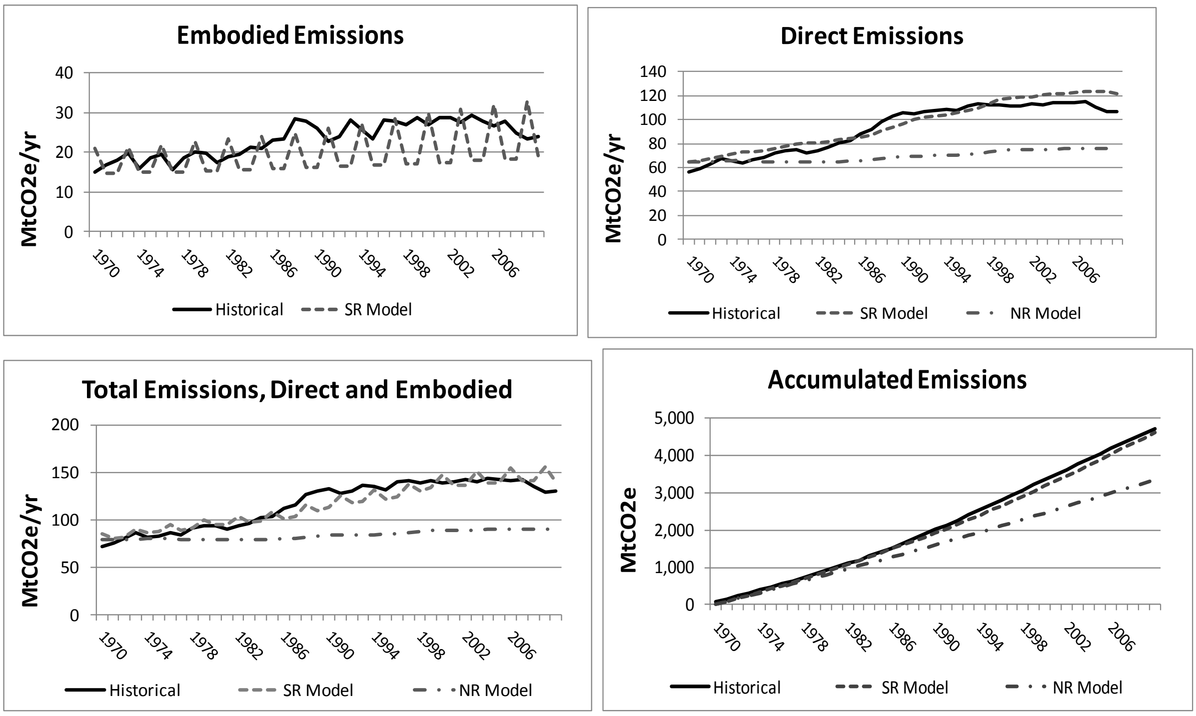

Figure 3: Total, direct and embodied CE trends ($MtCO_{2e}$) in the historical data, the Structural Rebound model, and the No Rebound model

Figure 4 shows the coupling (the ratio calculated in each year) between emissions and economic activity. This is one of two key indicators that show trends in the rate of decarbonization of the road transport sector. In the SR model the ratio falls by around a third; in the NR model emissions are decoupled by about half. The other key output is CE/person, a measure of the CO_{2e} intensity of road travel; this rises by around a half in the SR model but only by less than a tenth in the NR model.

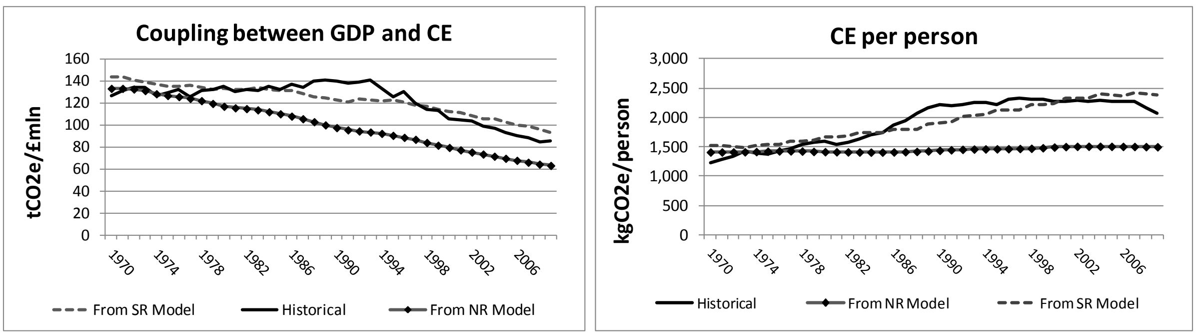

Figure 4: Trends in coupling between GDP and CE, and in CE per person, in the historical data, the Structural Rebound model, and the No Rebound model

Uncertainty Analysis

An uncertainty analysis was run that varied the four exogenous uncertainty variables described in Table 1 and shown in Figure 2 – Political Ideology, Science and EU Policy, International fuel markets, and GDP – by +/- 50%, within a multivariate sensitivity analysis, to see how the system might have responded to different exogenous influences in the historical period. These variables add variability to values for GDP, fuel expenses, rate of road building, and environmental regulation. The ranges of variance in CE/person and travel per person were much less than the variance in the input variables of +/- 50%, indicating that the dynamics of the model are most heavily influenced by the structure of the system, including the strength of its feedback loops. The distribution of CE/person values is skewed upwards, indicating that model dynamics will tend to produce higher CE values even when factors coming from outside the system are varying equally up or down.

Intervening With the System to Reduce CO_{2e} Emissions

Four interventions (described in Table 2) were added to the model, representing different policies typically carried out to achieve CE reductions. Interventions were added as dimensionless influences on model dynamics, reducing or increasing the rate of change for several flows and auxiliaries. The magnitude of the four interventions was set to vary between 1 and 10 during different model tests; however, this value is not comparable between the intervention types in terms of how much they impact system behavior, and so we discuss only the impacts of the interventions rather than the magnitudes at which they were set.

Intervention	Description	Policy Examples	How Implemented in the Model
Behavioral: Behavioral Change	Promotes the idea that people should travel less by private road transport, which reduces the growth in non-freight travel	Public awareness campaigns, social marketing	Reducing the annual growth in non-freight travel per person.
Technological: Investment in electric/low CO2e vehicles	Improves overall fleet efficiency	Improving reliability and affordability of electric vehicles and other non-internal combustion engine vehicles; accelerating efficiency improvements for petrol and diesel vehicles	Increasing the efficiency change rate that flows into the fleet efficiency stock
Economic: Cost of externalities multiplier	Provides a price signal to consumers that intervenes with the normal effects of demand supply economics in which reduced costs automatically lead to higher consumption	Policies could include road pricing, taxes on freight, and increasing taxes on high EI vehicles and fuel.	Increasing the price of vehicles and the retail price of fuel, and reducing the rate at which freight travel increases
Alternatives: Public investment in alternative transport modes	Reverses investment patterns towards private road travel and makes non-motorized and public transport more affordable and more attractive.	Subsidization of buses and trains, improving safety for pedestrians and cyclists, and improving the regulation of public transport.	Reducing the rate at which new roads are built in response to congestion, and reducing the growth in non- freight travel per person

Table 2: Details of the four interventions introduced to the historical and forecast Structural Rebound models to reduce Carbon Emissions, and how they are implemented in the models

Counteracting Structural Rebound with Interventions

The SR model was run as a multivariate sensitivity, with levels for each of the four interventions simultaneously varied through a Monte Carlo simulation. In 90% of the 10,000 cases that were run, the combined effect of the four interventions successfully reduced accumulated CE by 2010 to the same level as in the NR model or less. Figure 5 shows the effects on key variables for four sample cases from the simulation which have similar drops in accumulated CE. These cases were chosen as examples of intervention scenarios in which one of the interventions is inactive, allowing us to consider the necessity of each type of intervention. When one intervention is not active the other interventions must be more active to achieve the CE reductions, and this has an impact on system behavior from the perspective of consumers, in the cost of travel and the amount of travel, and for the rate of change in efficiency of vehicles.

No Technological Case: This case has no intervention to create *additional* improvement to fleet efficiency beyond what would happen due to investment by the supply chain, and it has the highest overall impact of the four minimal cases. It leads to travel cost increases and decreases in travel consumption of around a third, while efficiency gains are lower by a tenth compared to the SR historical model as the supply chain invests less due to less demand.

No Behavioral Case: This case has no intervention to directly dampen demand for travel. It shows an increase in the cost of travel and a drop in travel consumption of just over a quarter, and an increase in efficiency of around a tenth. There is still a large drop in consumption due to a price elasticity response to higher cost of travel.

No Alternatives Case: This case shows the highest increase in efficiency, about a quarter, needed to offset the lack of intervention to dampen travel consumption and road building. Consumption decreases by the least of the four cases, but is still over a quarter – due to a high level of Behavioral intervention and a small increase in the cost of travel.

No Economical Case: This case has the most balanced impacts of the four cases, with low cost increases and a lower drop in travel consumption than other cases, while there are gains in efficiency of almost a sixth. However, it has the lowest decoupling in CE/GDP.

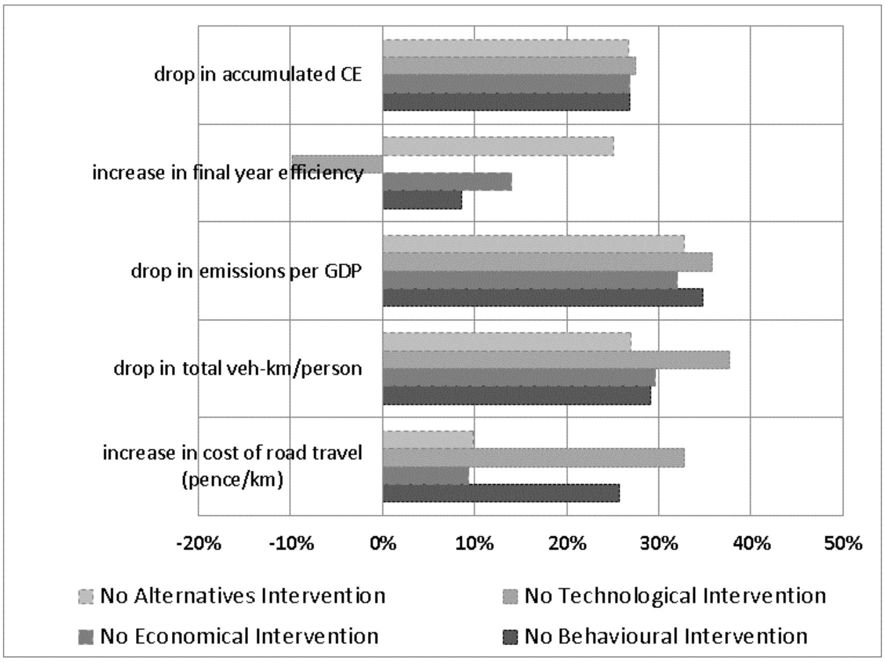

Figure 5: Percentage change in road travel costs, travel consumption and fleet efficiency, and the CE reductions and decoupling achieved, compared to the SR historical model, in four sample minimal intervention cases

Reaching Future CE Reduction Goals

In January 2014 the EU set a goal[iii] for CE reductions of 40% below 1990 levels by 2030. To determine what would be required to reach this goal within the road transport sector a forecast version of the model was built with the timeline extended to 2030. The key metric for the forecast model is CE/person, to remove the impact of uncertainty about future trends in population. CE/person in 1990 were 2191 $kgCO_{2e}$/year, and so the EU goal would be to reach 1315 $kgCO_{2e}$/year or lower by 2030. The four interventions were added to the forecast model but only made active within the forecast period (between 2011 and 2030). When interventions were added in a Monte Carlo multivariate sensitivity run, around a third of the 10,000 cases met or exceeded the EU goal by 2030.

Figure 6 shows the effects on key variables of four example cases of minimal intervention that meet the goal, plotted against the SR forecast. There was at least one successful case with no intervention for each of the four except for the technological intervention; the minimal technological case included a small amount of intervention. Trends in CE/person are fairly similar for the four sample cases but other impacts differ considerably. The largest drop in travel consumption is in the No Technological intervention case, because less CE are reduced through efficiency gains. Rises in the cost of road travel are highest in the No Technological and No Alternatives cases. In the No Economical case, travel costs actually go down due to higher gains in efficiency. The highest efficiency gains are for the No Economical intervention case.

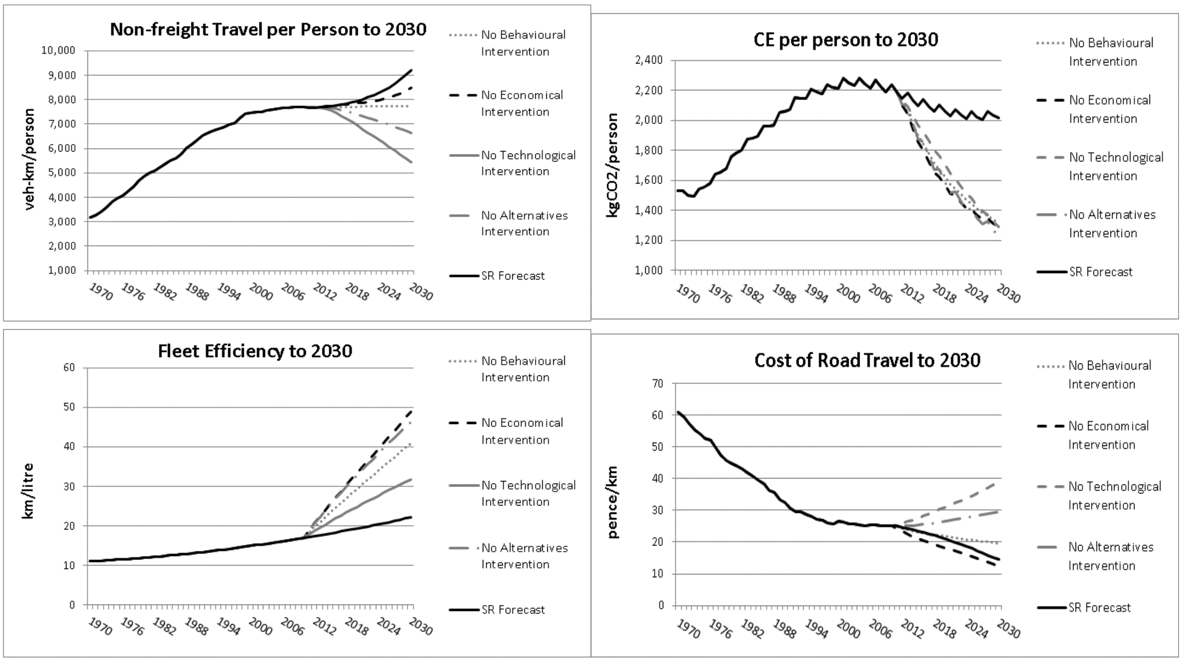

Figure 6: Four sample minimal intervention cases that meet the EU goal by 2030; trend-lines show the relative impact on road travel cost, consumption and efficiency over time, and the CE/person reductions

Discussion

This section provides a discussion of the model results and their application to the wider agenda of reducing resource use.

The Size of the JP Effect: If we assume that the NR model represents what would have happened without JP then the change in key variable values provides an estimate of the size of the JP effect in the historical period. Estimated effects include: non-freight travel rising by about half and freight travel by a fifth; fleet efficiency rising by around a tenth; reductions in the cost of road travel of a quarter; and a rise in accumulated CE of a third.

The Role of Efficiency: One of the characteristics of JP is that efficiency does not always lead to resource savings in the long term. This is exemplified when the Technological intervention was applied singularly to the SR forecast model. When the intervention was set high enough to increase efficiency gains to three times higher than the forecast model, on an annual average basis, there was a drop in accumulated CE of only about a tenth - indicating a poor return on investment in efficiency if reduced CE are the goal.

Who Pays for CE Reductions: The relative gains and losses in the intervention scenarios from the historical and forecast models show that the secondary effects of interventions to reduce CE will have to be borne either by individuals through reductions in travel and/or increases in the cost of travel, or by the public sector and industry through investing in alternative transport modes and higher efficiency vehicles – or, more likely, through some combination of the two.

Decoupling Metrics: Many cases in the model showed a decrease in GDP-CE coupling but an absolute increase in CE/person. The GDP-CE coupling metric provides a gauge of how large changes will need to be to meet EU goals. GDP-CE coupling drops by around a third in the historical period lasting forty years, while in the set of cases that meet the EU goal by 2030, during the twenty year period 2010 to 2030 coupling drops by about a half - a rate that is over three times the historical period on an average annual basis.

Rates of Efficiency Change in the Future: In the historical model, changes to fleet efficiency were estimated by a simple comparison of values in the final year of the model. In the forecast model, fleet efficiency was expressed as an average annual increase in efficiency, based on compound annual percentage increases between 2011 and 2030. This approach was taken so that model results could be compared with the IEA's technology roadmap for the fuel economy of road vehicles, which forecasts an average of 2.7% in annual improvement in efficiency of vehicles between 2012 and 2030 (International Energy Agency 2012). Comparing this annual efficiency measurement we find efficiency gains in the SR forecast model much lower than the roadmap at 1.4%, while efficiency gains within the set of cases that meet the EU goal are all higher than the road map, with a minimum of 3.2%. This result indicates that to ensure the goal is met, either technology efficiency has to rise much faster than industry is planning for, or some kind of structural change to the system may need to occur.

The role of government: The model indicates that to achieve the EU goal in the road transport sector would require a significant amount of both investment by industry and transport policy changes by government. Up to now, taking such a strong stance has not been politically feasible in the UK – as evidenced by the government's inability to implement their own transport policy in the 1990s (Docherty & Shaw 2011). We find it highly unlikely that the EU goal will be met by 2030 unless there is a change in priorities towards reducing EI within both society and government.

Policy Resistance: If the intention of improving efficiency were to reduce resource use then the existence of JP could be seen as evidence of "policy resistance" (Stepp et al. 2009), which Sterman describes as *'the tendency for interventions to be defeated by the response of the system to the intervention itself'* (2000). Meadows describes this as a "system trap" which can happen when '*goals of subsystems are different from and inconsistent with each other*' (Meadows & Wright 2009). One of Meadows' recommendations for a way out of the trap is to work towards mutually agreeable ways of meeting all the subsystem goals, or to define *'larger and more important goals that everyone can pull toward together'* (ibid.).

Conclusions

This paper set out to develop a dynamic and more endogenous understanding of Jevons' Paradox than currently exists, through developing a theory of what causes it, modeling the theory with system dynamics in an application of the UK's road transport system between 1970 and 2010, and applying interventions to the model. The model, based on the theory, mixes societal, technical, and economic factors. As it stands, the model only indicates broad trends, but it does provide an indication of the historical size of the JP effect in the road transport sector and the likely response of the system to combinations of interventions designed to mitigate CE.

Model results indicate that the approximate impact of JP within the historical period was a rise in travel consumption of about a half and a rise in CO_{2e} emissions of about a third. Applying four types of CE reduction interventions to the historical model, with variable combinations of impact, revealed that in order to counteract JP, impacts would need to be borne by individuals through reductions in travel consumption and increased cost of travel, and/or by the public sector and industry through investing in alternative transport modes and higher efficiency vehicles. A forecast model to 2030 was used to estimate whether the EU goal of a 40% drop in CO_{2e} emissions by 2030 is achievable in the road transport sector. The results indicate that higher increases in fleet efficiency than are currently forecast, costlier travel, and a significant reduction in travel consumption would all be required.

The theory building and SD modelling presented in this paper have provided several insights into the workings of JP and ways to intervene with it. The theory provides only one possible hypothesis about the underlying dynamics at play in real world systems when JP occurs. The SR historical model behavior correlates approximately with historical data, which corroborates but does not guarantee that the hypothesis embodied in the model represents the dynamics of the real world. When social norms and infrastructure growth are removed from the SR model to represent a No Rebound case, the model shows much lower growth in CE than observed, indicating that the No Rebound model cannot represent the real world.

The causal theory and model presented in this paper provide a fresh perspective on a long-studied problem about which there is still much uncertainty. Further work could include model additions that would allow more nuanced exploration of macro-economic factors, and the inclusion of trade-offs between different travel modes, such as between private, public or non-motorized transport. These changes might improve the accuracy with which the model tracks historical values, particularly travel consumption in the years after 2007. The model would also benefit from further work on intervention testing which is currently only at the level of introducing general influences; a more detailed model allowing quantitative parameterization of such interventions would allow further exploration of their effectiveness, likely cost, and mutual interactions.

Findings from the modeling highlight the need to implement a system of interventions that can influence the strength and direction of each of the feedback loops within the system being intervened with, if CO_{2e} emissions are to be more reliably reduced than they are at present. Single interventions are much less likely to succeed and are in fact less efficient at producing the desired results. And because the system is constantly evolving, intervening with it requires a responsive and holistic approach, while maintaining focus on a long-term goal.

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Supporting Information

Additional supporting information may be found in the online version of the article. This includes a full SD model diagram, data sources for the model, and more details on the model design.

Notes

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[i] Causal Loop Diagramming is a problem structuring tool which can be used to visually represent the causal relationships between elements in a system (Spector et al. 2001). It represents influence but is not quantitative and so causal loop diagrams cannot be simulated.

[ii] Vensim is produced by Ventana Systems. http://vensim.com/

[iii] http://europa.eu/rapid/press-release_IP-14-54_en.htm