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Simulation of Transitions Towards Emission-Free Urban Transport

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Abstract

This article presents a simulation model that depicts transport user choice in urban areas among different types of private cars and public transport. The model is used to examine the effects of different policies to aid reduction of greenhouse gas emissions. Simulation results reveal that policies directed towards the adoption of new private car technologies and towards public transport cannot be analysed separately. Policies must be designed in unison in a way that they work well together and do not undermine each other's effects. For example, policies targeting electric car adoption may reduce public transport ridership and not advance the overall vision of emission free transport.

Introduction

Climate change is a major driver that motivates the aim to decrease emissions caused by transport. The EU White paper on transport (European Commission 2011) includes aims to reduce greenhouse gas emissions and phase out the use of conventional combustion engine cars in urban transport by 2050. Many of the on-going efforts in transport research focus on technology-oriented approaches. These may focus on e.g. comparisons between performance characteristics of conventional cars and electric vehicles or potential volumes of the transport biofuel market. Regarding public transport, new intelligent technologies provide opportunities for information provision and location based services.

The importance of better understanding transport user choices and preferences cannot, however, be ignored. Accordingly, approaches considering user choices have recently gained interest. For example, Tran et al. (In press) have chosen probabilistic Monte Carlo simulation in combination with scenarios to model adoption of alternative fuel vehicles. There are also many existing system dynamics models that address the adoption of new products and services (Bass 1969, Milling 2002, Maier 1998, Sterman 2000 ch9), also regarding the car industry (e.g. Struben & Sterman 2008, Bosshardt et al. 2008). While some models address also the organizational processes of the car industry (Bouza et al. 2009), these existing models do not consider the effects of the new technologies on broader transport planning issues. In separate work, Sterman (2000, Ch. 5) discusses the role of issues such as road building in making private car use attractive and causing a public transport death spiral. Similar unintended consequences might also result from policies aimed at increasing the adoption of new private car technologies.

In this article, we take a more comprehensive scope covering not only the purchase decision of different vehicle and fuel technologies but also the daily choice of transport mode between private and public transport. This broader view is also in line with the recently identified goal in transportation research to see impact assessments as tools to help in the negotiation and deliberation process through which socially desirable transport actions are identified (Tuominen 2009). Currently, impact assessments in transport are mainly used to assess value for money, which has been criticized as too narrow and biased (Meyer & Miller 2001, Short & Kopp 2005).

The EU targets to reduce greenhouse gas emissions in transport need to be effectuated by national governments and authorities. Nilsson et al. (2012), for example, have concluded that while EU level governance has a major role regarding biofuel and hybrid-electric vehicle technologies, the national level has a lot more impact. Whereas the national level can already give momentum for concrete actions and changes, the involvement of local stakeholders, most importantly cities themselves, is crucial. The city authorities could actually be the stakeholder to step up and claim ownership of the vision. This would mean direct commitment to the target on the local level, enabling effective locally executed policy measures to steer the way towards it. Such views of the roles of cities in urban socio-technical transitions have been explored by e.g. Hodson & Marvin (2010). They have observed that multi-level perspective (Geels 2004) and transitions approaches typically remain somewhat underdeveloped in spatial scale and limit themselves implicitly to national level. Further, they suggest that cities should not be seen merely as sites receiving transition initiatives in the multi-level governance (in our case all the way from the EU and national levels to regional and local levels), and we aim to elaborate this train of thought by exploring the city as an active stakeholder with major role in initiating and leading the way towards the vision.

Measures to increase public transport usage include the following: 1) Soft measures target to reduce transport system end users' transport demand and to increase their willingness to consider public transport as the most feasible means of transport. Measures include workplace and school travel plans, personalised travel planning, travel awareness campaigns, teleworking, teleconferencing and measures to brighten up public transport image e.g. with better public transport information and marketing. 2) Governance measures are systemic in nature and relate to the organisation of transport sector actors and institutions in general and to organising and regulating public transport services in particular. 3) Infrastructure measures focus on building new public transport infrastructure. New railway infrastructure is here the key for increased service level of public transport. However, it needs to be accompanied with functional bus transport and walking and cycling networks, nodes and infrastructure (e.g. location of and accessibility to bus stops, park & ride areas, etc.). 4) Intelligent transport technologies and services (ITS) measures include common payment system for the Helsinki region and affordable public transport ticket products. These are complemented with introduction of GPS based road charging to reduce private car travel. 5) Measures targeted to public transport vehicles highlight the importance of increased R&D funding for clean and energy efficient urban bus fleet. In addition, green public procurement is emphasised.

Regarding the adoption of new technologies, there is a need for strategic coalition building initiatives which bring together actors such as car makers, legislators, infrastructure planners, researchers developing new technologies, as well as different companies that specialize in service infrastructure and energy provision. The construction of legal and regulatory frameworks regarding biofuels is steadily developing already. Market and price mechanisms, as well as the implementation of different kinds of subsidies and tax incentives are also important. Precompetitive procurement, in other words public demand, can provide an important testing environment and lead market for new solutions related to electric vehicles. Public procurement strategies are essential in the emergence phase. In this sense, public procurement could also provide an important first reference for new solutions. Empirical examples of innovation diffusion have proved that getting the first reference is often critical for the subsequent success of new solutions, products and services.

There is also a need to use R&D funding for technology development because widespread replacement of combustion motor vehicles is hardly possible with current technology. In a country like Finland, an additional challenge is caused by rather long distances which set specific requirements to energy capacity and charging infrastructure of battery electric vehicles (c.f. Nylund 2011). Therefore, particularly during short to middle term, plug-in hybrid electric vehicles combining battery electric technology to combustion engine can turn out to be a cost effective way to reduce emissions of traffic. Public support for R&D efforts should last long enough to ensure that a knowledge infrastructure and knowledge intensive companies specialising in electric vehicle transport are in place and start to produce results on their own. Infrastructure development policies are important both for the diffusion of electric vehicles and biofuels. Regarding biofuels, there are local, national and transnational decisions to build infrastructure for fuel production and distribution. Regarding electric cars, necessary infrastructure includes charging stations.

Model description

The context of our analysis is the Helsinki metropolitan area, and the time frame is until 2050. The simulation model depicts user choice of means of transport, both in the short term regarding individual trips, and also in the long term regarding the purchase of different types of cars. The approach is in line with the new clean fuel strategy of the European Commission (European Commission 2013). The model assumes that three factors affect the choice of a particular mode of transport: travel time, costs, and awareness.

We consider the role of three solutions to the sustainability problem in transport: public transport, electric vehicles, and biofuels. Electric vehicles and biofuels were judged the most feasible and thus the most interesting technological solutions to replace conventional gasoline and diesel driven vehicles. Other similar alternatives discussed included vehicles fuelled by hydrogen or waste derivatives. In addition, radical improvements in vehicle energy efficiency and powertrain solutions could have been studied as such or when combined to the previously mentioned technologies. The general reduction of motorized travel due to walking, cycling, or substituting virtual solutions was excluded from the model scope.

The main feedback loops of the model, shown in Figure 1, are:

- Awareness of public transport and cars (reinforcing feedbacks R1 and R2): An increasing trip fraction by a particular means of transport increases its familiarity in the population, thus making its use more common.
- Congestion (balancing feedback B1): Car use causes congestion. This increases travel time by car and makes car use less attractive.
- Build roads (reinforcing feedback R3): Congestion increases the pressure to build more road capacity and reduce the trip time by car.
- Population movement (balancing feedback B2): Congestion makes areas with access to public transport more attractive, thus lowering the trip fraction by car.

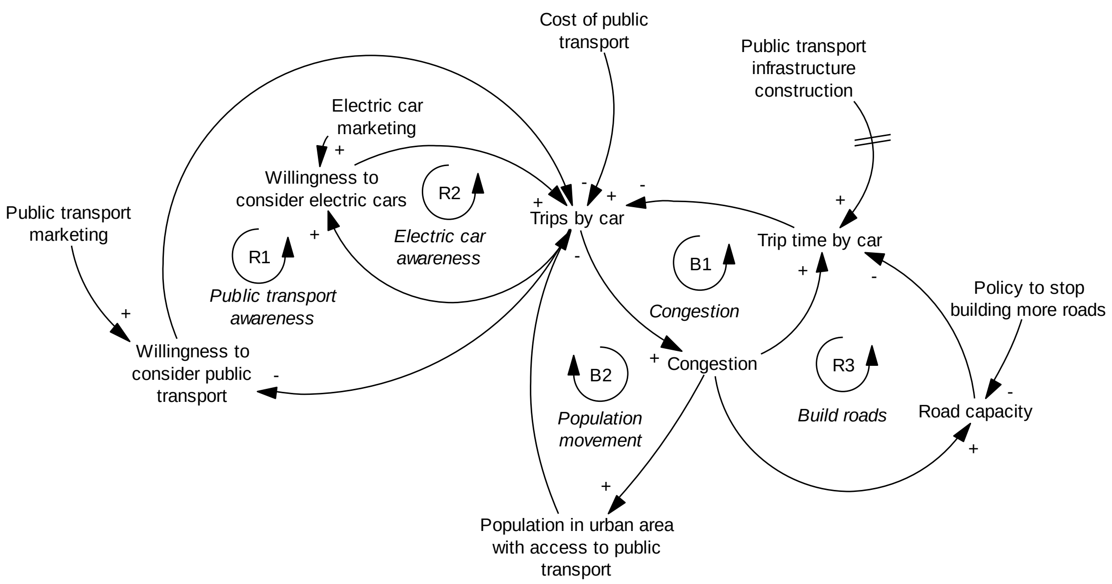


Figure 1. Causal loop diagram

The simulation model includes three means of transport $x, y, z \in \{\text{Public, regular car, electric car}\}$ [1].

Choice of means of transport

The choice of means of transport is divided into short term and long term choices. In the short term, car owners have the option of either to make an individual trip by private car or use public transport. The attractiveness of a trip by public transport use in the short term for users of transport mode *x* depends on the effects of travel time and trip cost on attractiveness, the maximum trip fraction possible by public transport (dependent on public transport network coverage), and people's willingness to consider public transport:

$$\text{PublicAttrShort}_\text{x} = (1 - \text{CarTimeAttrShort}_\text{x} \cdot \text{CarCostAttrShort}_\text{x}) \cdot \text{MaxTripFraction}_\text{public} \cdot \text{WtC}_\text{x public} \tag{1}$$

The trip fraction of the different cars and public transport depend on the short term attractiveness of public transport:

$$\text{TripFraction}_{\text{x}\in\text{cars}} = \text{MaxTripFraction}_\text{x} \cdot (1 - \text{PublicAttrShort}_\text{x}) \tag{2}$$

$$\text{TripFraction}_\text{public} = (1 - \textstyle\sum_{\text{x}\in\text{cars}} \text{MaxTripFraction}_\text{x}) + \textstyle\sum_{\text{x}\in\text{cars}} \text{MaxTripFraction}_\text{x} \cdot \text{PublicAttrShort}_\text{x} \tag{3}$$

In the equations above, the maximum trip fraction of each means of transport is dependent on the user fraction (i.e. ownership fraction) for cars and by the public transport coverage for public transport:

$$\text{MaxTripFract}_{\text{x}\in\text{cars}} = \text{UserFraction}_\text{x} \tag{4}$$

$$\text{MaxTripFract}_\text{public} = \text{InfraRange}_\text{public} \tag{5}$$

The number of car trips per day is determined by the exogenously determined total number of trips and the fraction of trips by car:

$$\text{TripsByCar} = \text{Trips} \cdot \textstyle\sum_{\text{x}\in\text{cars}} \text{TripFraction}_\text{x} \cdot \text{CarsPerTrip} \tag{6}$$

In the long term, people decide whether to purchase a car and which type of car to purchase. Like short term attractiveness, the long term attractiveness is determined

[1] Some equations also use the following sub range: cars={regular car, electric car}

based on the relative costs and travel times in addition to the willingness to consider. Whereas the short term attractiveness depends on the trip cost, the long term attractiveness is determined by the yearly costs.

The attractiveness of means of transport y for users of mode x:

$$\mathrm{AttrLong}_{xy} = \quad \mathrm{WtC}_{xy} \cdot \mathrm{InfraRange}_{y} \cdot \mathrm{TimeAttrLong}_{y} \cdot \mathrm{CostAttrLong}_{y} \tag{7}$$

To calculate the average attractiveness of y, a weighted average is used:

$$\mathrm{AvAttrLong}_{y} = \quad \sum_{x} \mathrm{UserFraction}_{x} \cdot \mathrm{AttrLong}_{xy} \tag{8}$$

The purchase fraction refers to the fraction of population who are willing to own a certain type of car.

$$\mathrm{PurchaseFraction}_{x \in cars} = \quad \mathrm{MinCarFraction} \cdot \frac{\mathrm{AvAttrLong}_{x}}{\sum_{x \in cars} \mathrm{AvAttrLong}_{x}} + \quad (1 - \mathrm{MinCarFraction}) \cdot \frac{\mathrm{AvAttrLong}_{x}}{\sum_{x} \mathrm{AvAttrLong}_{x}} \tag{9}$$

In the equation above, $\mathrm{MinCarFraction}$ is the minimum fraction of the population who need cars irrespective of the quality of public transport in the urban area. The first term of the equation divides car purchases between regular and electric cars based on their attractiveness in the population who need a car in any case. The second term of the equation considers also the attractiveness of public transport for the remaining fraction of the population who do necessarily need a car.

The number of cars changes through car sales and discards:

$$\frac{d}{dt}\mathrm{CarStock}_{x \in cars} = \quad \mathrm{Sales}_{x} - \mathrm{Discards}_{x} \tag{10}$$

$$\mathrm{Sales}_{x \in cars} = \quad \frac{\mathrm{PurchaseFraction}_{x} \cdot \mathrm{Population}}{\mathrm{PeoplePerCar} \cdot \mathrm{Lifetime}} \tag{11}$$

$$\mathrm{Discards}_{x \in cars} = \quad \frac{\mathrm{CarStock}_{x}}{\mathrm{Lifetime}} \tag{12}$$

The number of car users is calculated based on the stock of cars.

$$\mathrm{Users}_{x \in cars} = \quad \mathrm{CarStock}_{x} \cdot \mathrm{PeoplePerCar} \tag{13}$$

The rest of the population are considered public transport users:

$$\mathrm{Users}_{public} = \quad \max(0, \mathrm{Population} - \sum_{x \in cars} \mathrm{CarStock}_{x} \cdot \mathrm{PeoplePerCar}) \tag{14}$$

Willingness to consider means of transport

Willingness to consider (WtC) reflects users' awareness of the different available means of transport. We have drawn from the model by Struben & Sterman (2008), who have used the willingness to consider construct to examine the adoption of alternative fuel vehicles. In their model, WtC depends on the size of the installed base of a particular car type relative to the total installed base of all cars. In our model, we assume instead that WtC depends on the trip fraction of the means of transport. The reason for this is twofold: First, we consider not only the adoption of different types of cars but also the use of public transport. Second, car owners can make trips by public transport.

In the model, $\mathrm{WtC_{xy}}$, i.e. the willingness of users of means of transport x to consider y, either in the short term when choosing a means of transport for an individual trip, or in the long term whether to own a car, is dependent on exposure and the decay rate:

$$\frac{\mathrm{d}}{\mathrm{dt}}\mathrm{WtC_{xy}} = \mathrm{Exposure_{xy}} \cdot \left(1 - \mathrm{WtC_{xy}}\right) - \mathrm{WtCDecay_{xy}} \cdot \mathrm{WtC_{xy}} \tag{15}$$

The total exposure is the sum of marketing and word of mouth exposure:

$$\mathrm{Exposure_{xy}} = \mathrm{Marketing_{y}} + \mathrm{DirectWOM_{xy}} + \mathrm{IndirectWOM_{xy}} \tag{16}$$

The effect of marketing is an exogenous input to the model. Word of mouth exposure can be divided into direct and indirect. In direct exposure, people learn about a means of transport from users of the same means of transport, while indirect exposure refers to learning from non-users.

The exposure by word of mouth is calculated as follows:

$$\mathrm{DirectWOM_{xy}} = \mathrm{ContactRate_{xyz}} \cdot \mathrm{WtC_{yy}} \cdot \mathrm{TripFraction_{y}} \tag{17}$$

$$\mathrm{IndirectWOM_{xy}} = \sum_{z \neq y} \mathrm{ContactRate_{xyz}} \cdot \mathrm{WtC_{zy}} \cdot \mathrm{TripFraction_{y}} \tag{18}$$

In the equations above, $\mathrm{ContactRate_{xyz}}$ refers to the word of mouth contact rate for users of means of transport x to hear information about y from users of z.

Constant exposure is needed for a particular means of transport. If not, WtC decays:

$$\mathrm{WtCDecay_{xy}} = \mathrm{MaxWtCDecay} \cdot \frac{e^{-4\varepsilon\cdot(\mathrm{Exposure_{xy}} - \mathrm{RefExposure})}}{1+e^{-4\varepsilon\cdot(\mathrm{Exposure_{xy}} - \mathrm{RefExposure})}} \tag{19}$$

where $\varepsilon = \frac{1}{2\cdot\mathrm{RefExposure}}$ is the slope of WtC decay rate at the reference rate. For details, see Struben & Sterman (2008).

Effects of travel time and costs on attractiveness

In the short term, the time and cost attractiveness of a trip by car is dependent on its relative trip time and relative costs.

$$\mathrm{CarTimeAttrShort}_{x\in\mathrm{cars}} = \mathrm{f}\left(\xi^{\mathrm{time}} \cdot \frac{\mathrm{PerceivedTripTime}_x - \mathrm{RefTripTime}}{\mathrm{RefTripTime}}\right) \tag{20}$$

$$\mathrm{CarCostAttrShort}_{x\in\mathrm{cars}} = \mathrm{f}\left(\xi^{\mathrm{cost}} \cdot \frac{\mathrm{TripCost}_x - \mathrm{RefTripCost}}{\mathrm{RefTripCost}}\right) \tag{21}$$

For non-car owners, the short term time and cost attractiveness of cars are set to zero.

$$\mathrm{CarTimeAttrShort}_{\mathrm{public}} = 0 \tag{22}$$

$$\mathrm{CarCostAttrShort}_{\mathrm{public}} = 0 \tag{23}$$

In the long term, the time attractiveness of each means of transport is calculated as follows:

$$\mathrm{TimeAttrLong}_x = f\left(\xi^{\mathrm{time}} \cdot \frac{\mathrm{PerceivedTripTime}_x - \mathrm{RefTripTime}}{\mathrm{RefTripTime}}\right) \tag{24}$$

$$\mathrm{CostAttrLong}_x = f\left(\xi^{\mathrm{cost}} \cdot \frac{\mathrm{YearlyCost}_x - \mathrm{RefYearlyCost}}{\mathrm{RefYearlyCost}}\right) \tag{25}$$

Logistic function $f(t) = \frac{1}{1+e^t}$ is used to model the effects on time and cost on attractiveness. This has the properties $f(-\infty) = 1, f(0) = 0.5, f(\infty) = 0$. Parameters ξ^{time} and ξ^{cost} are the sensitivities of utility to time and cost.

Trip costs and yearly costs are determined exogenously. The yearly cost of public transport use is calculated as follows:

$$\mathrm{YearlyCost}_{\mathrm{public}} = \mathrm{TripCost}_{\mathrm{public}} \cdot \mathrm{TripsPerPerson} \cdot \mathrm{DaysPerYear} \tag{26}$$

For car use, the purchase cost is also included in the yearly costs:

$$\mathrm{YearlyCost}_{x\in\mathrm{cars}} = \mathrm{TripCost}_x \cdot \mathrm{TripsPerPerson} \cdot \mathrm{DaysPerYear} + \frac{\mathrm{CarPrice}_x}{\mathrm{Lifetime} \cdot \mathrm{PeoplePerCar}} \tag{27}$$

The travel times are assumed to depend on the level of road congestion.

The reference values for the yearly costs, trip costs, and trip times are calculated based on the weighted averages of the means of transport values. The delay in reference formation is modelled using exponential smoothing[2].

$$\mathrm{RefYearlyCost} = \mathrm{SMOOTH}\left(\sum_x \mathrm{UserFraction}_x \cdot \mathrm{YearlyCost}_x, \tau^{\mathrm{reference}}\right) \tag{28}$$

$$\mathrm{RefTripCost} = \mathrm{SMOOTHI}\left(\sum_x \mathrm{TripFraction}_x \cdot \mathrm{TripCost}_x, \tau^{\mathrm{reference}}, \mathrm{RefTripCost}(0)\right) \tag{29}$$

$$\mathrm{RefTripTime} = \mathrm{SMOOTHI}\left(\sum_x \mathrm{TripFraction}_x \cdot \mathrm{TripTime}_x, \tau^{\mathrm{reference}}, \mathrm{RefTripTime}(0)\right) \tag{30}$$

Trip time

The perceived trip time depends on an exogenously determined base trip time, $\mathrm{TripTime}_x^0$, and the effect of congestion on travel time. Exponential smoothing is used to model the delay in travel time perception:

$$\mathrm{PerceivedTripTime}_x = \mathrm{SMOOTHI}(\mathrm{TripTime}_x^0 \cdot \mathrm{CongestionEffectOnTime}_x, \tau^{\mathrm{p}}, \mathrm{PerceivedTripTime}_x(0)) \tag{31}$$

Congestion, i.e. road utilization, is assumed to depend only on the trips by car:

$$\mathrm{Congestion} = \frac{\mathrm{TripsByCar}}{\mathrm{RoadCapacity}} \tag{32}$$

Congestion is assumed to increase only the travel time by car, not public transport:

$$\mathrm{CongestionEffectOnTime}_{\mathrm{public}} = 1 \tag{33}$$

$$\mathrm{CongestionEffectOnTime}_{x \in \mathrm{cars}} = \left(\max\left(1, \frac{\mathrm{Congestion}}{\mathrm{RefCongestion}}\right)\right)^{\alpha} \tag{34}$$

In the equation above, RefCongestion refers to the reference level of congestion above which travel time increases. Parameter α is the sensitivity of travel time to congestion.

An increasing level of congestion creates pressure to increase road capacity:

[2] SMOOTH(input, smooth time) and SMOOTHI(input, smooth time, initial value) refer to exponential smoothing functions of the Vensim simulation software.

$$\frac{d}{dt}\mathrm{RoadCapacity} = \frac{\left[\left(\frac{\mathrm{Congestion}}{\mathrm{RefCongestion}}\right)^{\beta} - 1\right] \cdot \mathrm{RoadCapacity}}{\tau^{\mathrm{roads}}} \tag{35}$$

The exponent β describes the sensitivity of road capacity to congestion.

Population

The total population is an exogenous time series that is used to calculate the total number of trips:

$$\mathrm{Trips} = \mathrm{Population} \cdot \mathrm{TripsPerPerson} \tag{36}$$

The population in the area is divided into two parts: people living in the inner urban area with access to public transport and people living in the outer area. For simplicity, we assume that the public transport network in the outer area is negligible. Note that this distinction between the inner and outer areas is not necessarily geographical. The inner area can also refer to geographically outer areas with good access to public transport, e.g. towns along railway lines.

The attractiveness of the outer region is determined by the reference attractiveness RefAttrOuter and the effect of the trip time by car on the outer region's attractiveness:

$$\mathrm{AttrOuter} = \mathrm{RefAttrOuter} \cdot \left[\frac{\sum_{x \in \mathrm{cars}} \mathrm{PerceivedTripTime} \cdot \mathrm{CarStock}_x}{\sum_{x \in \mathrm{cars}} \mathrm{RefHoursPerTrip} \cdot \mathrm{CarStock}_x}\right]^{\gamma} \tag{37}$$

Parameter γ is the sensitivity of attractiveness to trip time.

The infrastructure range of public transport is defined as the fraction of the population with access to public transport. It is calculated as a moving average of the inner area's attractiveness.

$$\mathrm{InfraRange}_{\mathrm{public}} = \mathrm{SMOOTH}(1 - \mathrm{AttrOuter}, \tau^{\mathrm{population}}) \tag{38}$$

For regular cars, the infrastructure coverage is assumed to be 100%, and for electric cars it is dependent on exogenous policy decisions.

Table 1 Parameters and initial conditions of the simulation model ("no policies" scenario)

Variable	Value	Unit	Description
C_{xyz}	1, $x = y$ 0.3, $x \neq y \land y = z$ (Direct) 0.11, $x \neq y \land y \neq z$ (Indirect)	$\frac{1}{Year}$	Contact rate

τ^{p}	1	$Year$	Perception time
τ^{roads}	5	$Year$	Time to build roads
$\mathrm{MinCarFract}$	0.5	$Dmnl$	Minimum fraction of car users
$\mathrm{CarPrice_x}$	N/A, 30000,60000	$\frac{€}{Car}$	Average purchase cost of a car
$\mathrm{CarsPerTrip}$	1	$\frac{Car}{Trip}$	Number of cars per trip
$\mathrm{DaysPerYear}$	365	$\frac{Day}{Year}$	Number of days per year
$\mathrm{RefExposure}$	0.13	$\frac{1}{Year}$	Reference rate of social exposure
$\mathrm{Lifetime}$	15	$Year$	Average car lifetime
$\mathrm{Marketing_x}$	0	$\frac{1}{Year}$	Value and duration varied in simulations
$\mathrm{TripCost_x}$	2,1,0.2	$\frac{€}{Trip}$	Cost of an individual trip
$\mathrm{TripTime_x^0}$	2,1,1	$\frac{Hour}{Trip}$	Base trip time
$\mathrm{MaxWtCDecay}$	1	$\frac{1}{Year}$	Maximum decay rate for willingness to consider
α	5	$Dmnl$	Sensitivity of travel time on congestion
β	3	$Dmnl$	Sensitivity of road capacity on congestion
$\mathrm{CarStock_{x\in cars}(0)}$	200000,0	Car	Initially no electric cars
$\mathrm{RoadCapacity(0)}$	925000	$\frac{Car}{Day}$	Initial road capacity
$\mathrm{WtC_{xy}(0)}$	$\begin{matrix} 1 & 0.5 & 0 \\ 0.9 & 1 & 0 \\ 0.9 & 1 & 0 \end{matrix}$	$Dmnl$	Initial value of willingness to consider
$\mathrm{TripsPerPerson}$	2.91	$\frac{Trip}{Person \cdot Day}$	Population: 1.34e6, Total trips per day: 3.9e6 => Trips per person: 2.91. Assumed that this ratio stays constant
$\tau^{population}$	5	$Year$	Time for population to move from one area to another
γ	0.5	$Dmnl$	Sensitivity of people moving from one area to another
$\mathrm{RefAttrOuter}$	0.25	$Dmnl$	Reference attractiveness of outer area
$\mathrm{RefHoursPerTrip}$	1	$Dmnl$	Reference travel time, influencing the attractiveness of the outer region
$\mathrm{InfraRange_{regularcar}}$	1	$Dmnl$	Full infrastructure range of regular cars is assumed
$\mathrm{RefTripCost(0)}$	1.75	$\frac{€}{Trip}$	Initial reference trip cost
$\mathrm{RefTripTime(0)}$	1.75	$\frac{Hour}{Trip}$	Initial reference trip time
$\mathrm{PeoplePerCar}$	2	$\frac{Person}{Car}$	Number of people per car
$\mathrm{RefCongestion}$	0.8	$Dmnl$	Reference road utilization
$\tau^{reference}$	2	$Year$	Time for reference formation
$\mathrm{PerceivedTripTime(0)}$	2,1.05,1.05	$\frac{Hour}{Trip}$	Initial perceived trip time. For cars slightly higher than base trip time because of congestion effect.
ξ^{time}	8	$Dmnl$	Sensitivity of utility to travel time
ξ^{cost}	2	$Dmnl$	Sensitivity of utility to cost. Assumed that $\xi^{time} > \xi^{cost}$

Simulation results

The main outputs of the model are the fraction of trips and number of users of each transport mode. Whereas in more typical technology-oriented approaches e.g.

alternative vehicle powertrains, fuels, and public transport provision are brought to the centre, in our model these are rather inputs that affect user choice. The effects of different policies are compared to the “no policies” (business-as-usual) scenario. Unless otherwise specified, the policies are implemented in the simulations at year 2012.

Public transport policies

Policy P1: Public transport infrastructure development (e.g. building new city railway line(s), upgrading current bus transport infrastructure and functionality of bus network and nodes) reduces travel time. The construction delay is assumed to be 10 years and the travel time is assumed to reduce by 50% to equal the minimum travel time by private car (Figure 2).

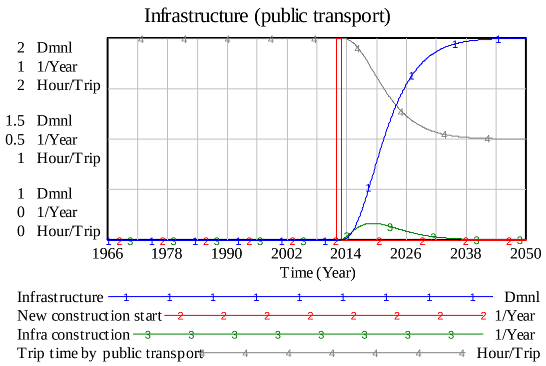


Figure 2 Public transport infrastructure development (exogenous input)

Policy P2: Public transport ticket price reductions can be made without delay. This policy lowers the trip cost of public transport from 2 €/Trip to 0.75 €/Trip, making it less expensive than regular car use.

Policy P3: Public transport awareness raising causes a rise in the willingness to consider with a delay. The policy refers to a group of awareness raising measures relating e.g. to mobility management and public transport image. In the model, the exogenous marketing effort for public transport is set to 0.1 starting from year 2018 with duration of 5 years.

Figure 3 and Figure 4 show the simulation results of policies directed towards public transport. P1 proposes major changes to the current public transport system and it is not surprising that it has a major positive impact on both public transport trips and users. P2 has similar impact on trip fractions as P1, but the impacts are realised sooner. However, the impacts on the number of users are very slight, which may indicate that the measure is not strong enough to evoke (permanent) modal shifts even though some changes in daily travel patterns may occur.

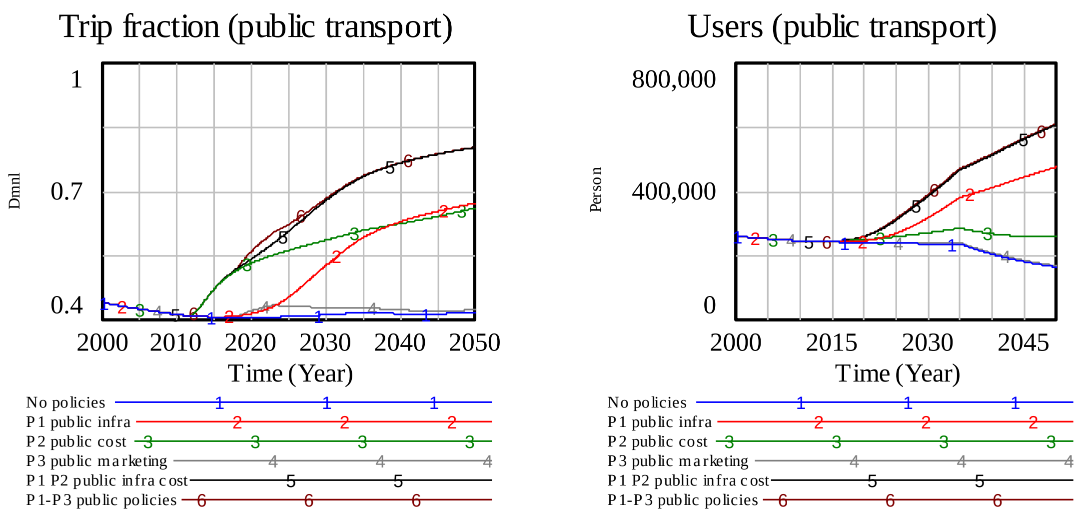


Figure 3 Effect of public transport policies on public transport use

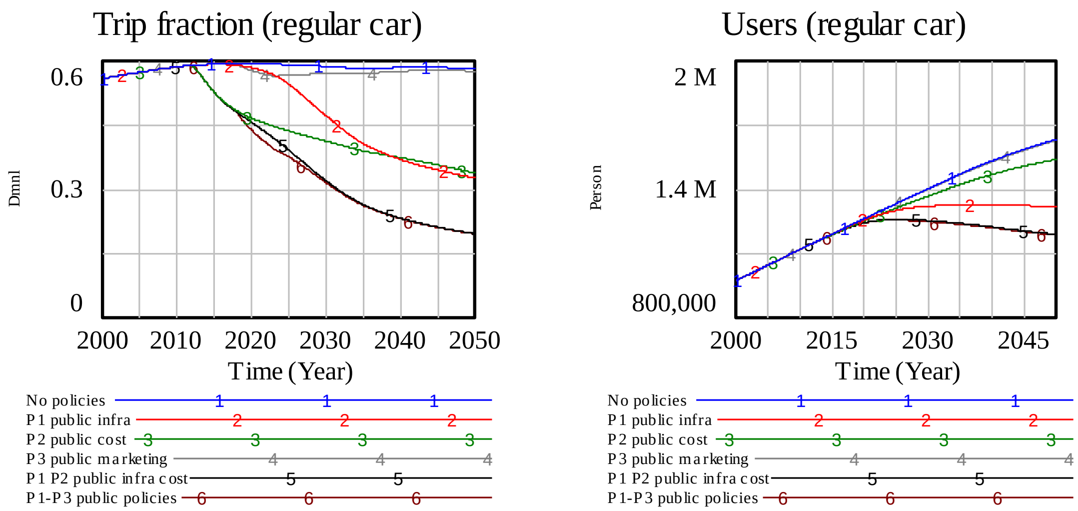


Figure 4 Effect of public transport policies on regular car use

Policies 1 and 2 together constitute a package that has significant impact on both fraction of trips and number of public transport users. The number of public transport users starts to increase slower than the modal share of public transport because of the inertia in the existing stock of cars. The number of private car users will stabilise to the current level. Keeping in mind the expected population growth (ca. 13% from 2010 to 2050), stabilisation can be seen as a positive result, since it means that the growth in total number of transport users is funnelled to public transport.

The results suggest that P3 alone is not very effective. Also, complementing policies P1 and P2 further with P3 does not make any noticeable difference to the impacts since the changes evoked by P1 and P2 are already significant. P3 might still be used to enhance the acceptability of the other policies.

Electric vehicle policies

Policy P4: Electric car infrastructure construction is modelled similarly as the development of public transport infrastructure. Once the policy decision has been made, the infrastructure develops with a delay. The level of electric car infrastructure has a limiting effect on the consumer attractiveness of electric cars. For simplicity, we assume that the relative performance of electric cars compared to regular cars develops at the same rate as the electric car infrastructure. As such, its effect is not separately modelled. Electric car infrastructure construction is started at year 2015. The construction delay is assumed to be 5 years (Figure 5).

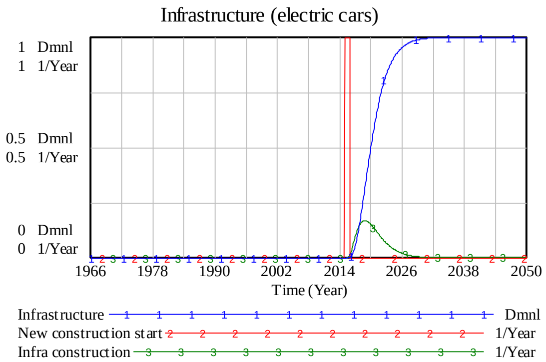
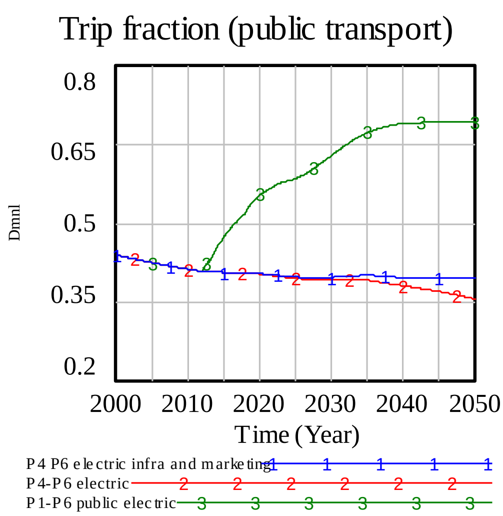


Figure 5. Electric car infrastructure development (exogenous input)

Policy P5: Electric car purchase subsidies lower the purchase price of an electric car to a consumer to the same level as the purchase of a regular car.

Policy P6: Electric car awareness raising causes a rise in the willingness to consider (with a delay). In the model, the exogenous marketing effect for electric cars is set to 1 starting at year 2018 for duration of 5 years.

Figure 6, Figure 7, and Figure 8 show the simulation results of policies directed towards electric cars:



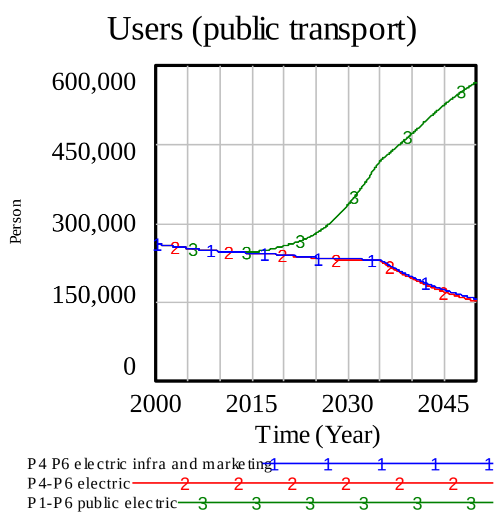


Figure 6 Effect of electric car policies on public transport use

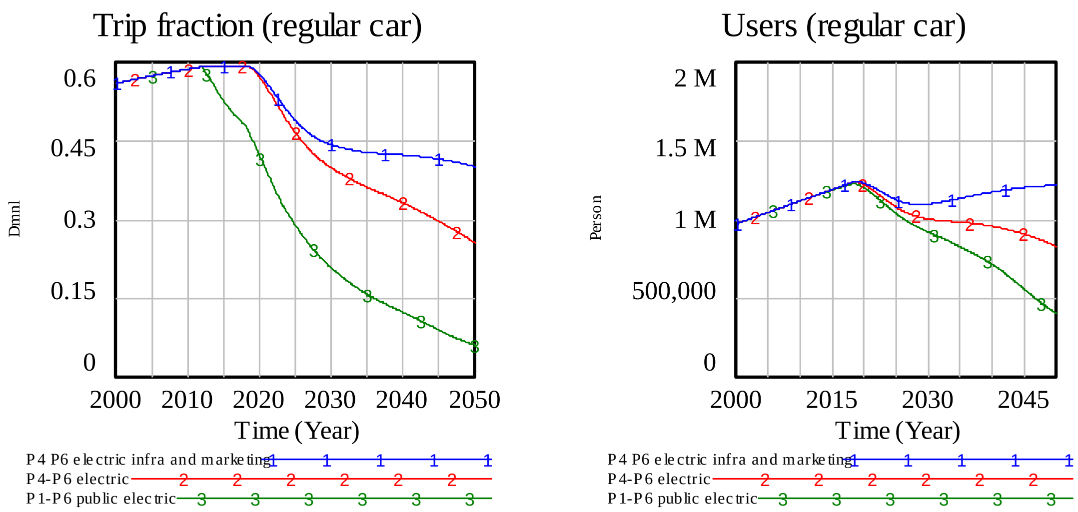


Figure 7 Effect of electric car policies on regular car use

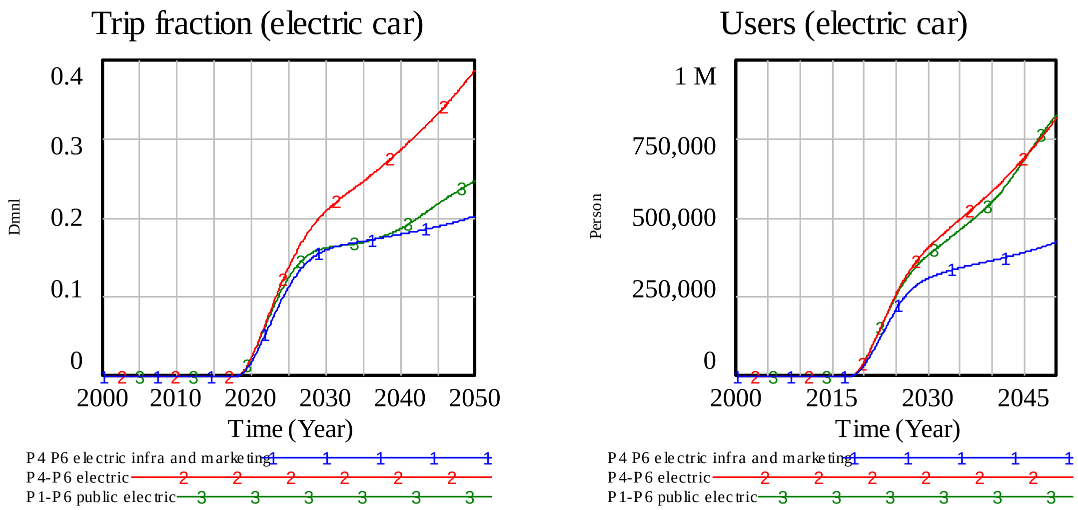


Figure 8 Effect of electric car policies on electric car use

The simulations show that if the policies tailored to support diffusion of electric vehicles – P4 and P6, but particularly the combination of the three measures of P4-P6 – are implemented, this will have an major positive impact both on fraction of trips accomplished by electric cars and number of users using electric cars in coming two to three decades. However, when comparing Figure 3 and Figure 6, we observe that policies targeting the adoption of electric cars also reduce the trip fraction of public transport. On the other hand, comparing Figure 4 and Figure 7 reveals that the trip fraction of regular cars is most effectively reduced using a combination of electric and public transport policies.

Biofuel policy

Policy P8: Investments to biofuel production capacity increases the availability of biofuels gradually such that the availability of biofuels by year 2040 will be approximately 50% of total demand. In the model, biofuels are assumed compatible with regular cars. Thus, the use of biofuel by regular car users does not require additional investments (unlike with electric cars that require purchasing a new type of car). Without biofuel availability, the trip cost of regular cars is assumed to rise due to the increasing price of oil. With biofuel availability, the cost of regular cars does not rise as quickly.

Figure 9, Figure 10, and Figure 11 show the results of the biofuel policy. Biofuels can be seen as an alternative to electric cars. Comparing Figure 8 and Figure 11 shows that the availability of biofuels can in fact slow down the adoption of electric cars. Likewise, the availability of biofuels can also decrease the use of public transport assuming that it reduces the cost of private cars.

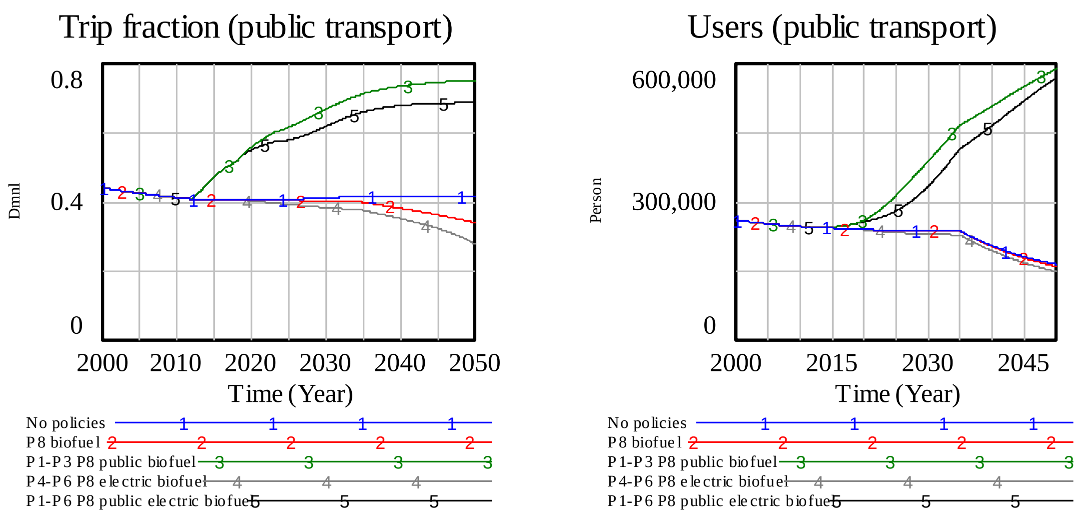


Figure 9 Effect of biofuel policy on public transport use

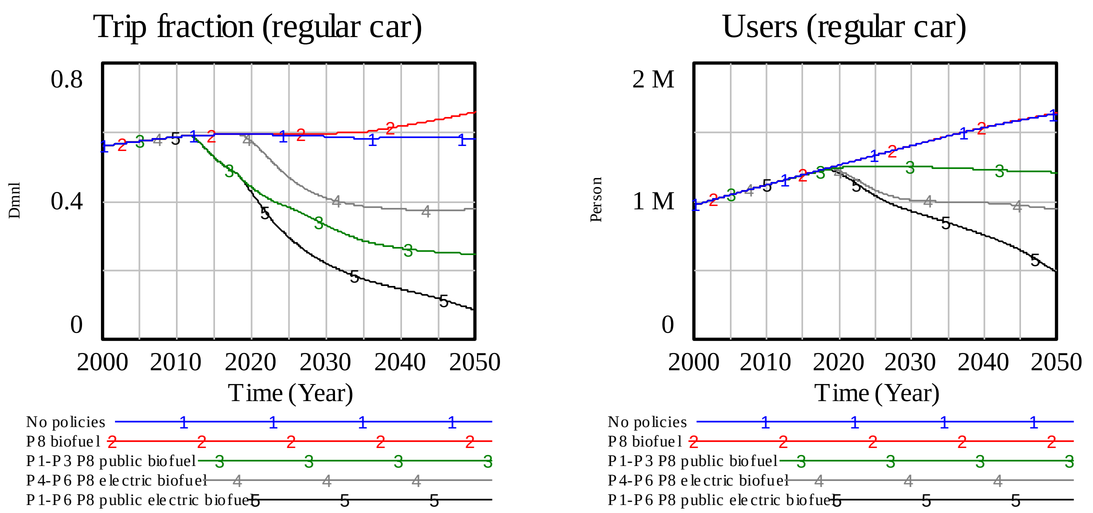


Figure 10 Effect of biofuel policy on regular car use

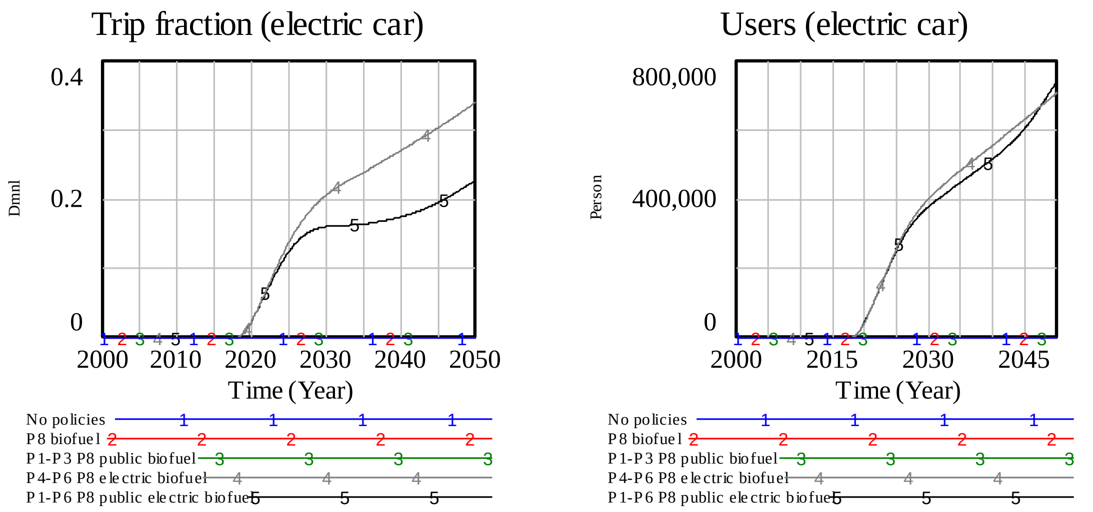


Figure 11 Effect of biofuel policy on electric car use

Road construction policy

Policy P7: Limitations on road construction cause the travel time by private car to increase and its relative attractiveness to decrease. This policy stops additional road construction after year 2012, thus switching off the feedback loop B2 in Figure 1.

Figure 12, Figure 13, and Figure 14 show the effects this policy. Limiting road construction alone has a positive effect on the trip fraction of public transport compared to the "no policies" scenario (red vs. blue lines in the figures). If all public transport policies are implemented, further limiting road construction (green vs. black lines) does not influence the trip fraction of the different transport modes. The reason is that the public transport policies already decrease congestion and the pressure to build more roads. However, if electric car policies are implemented instead of public transport policies, limiting road construction has an effect (grey vs. brown lines). In this case, limiting road construction decreases the trip fraction and users of private cars.

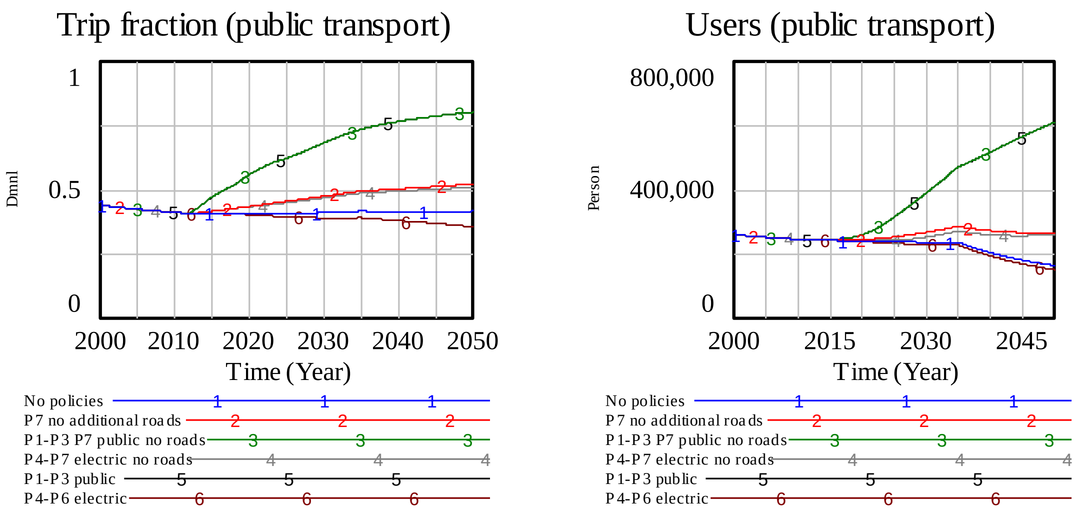


Figure 12 Effect of road building limitations on public transport use

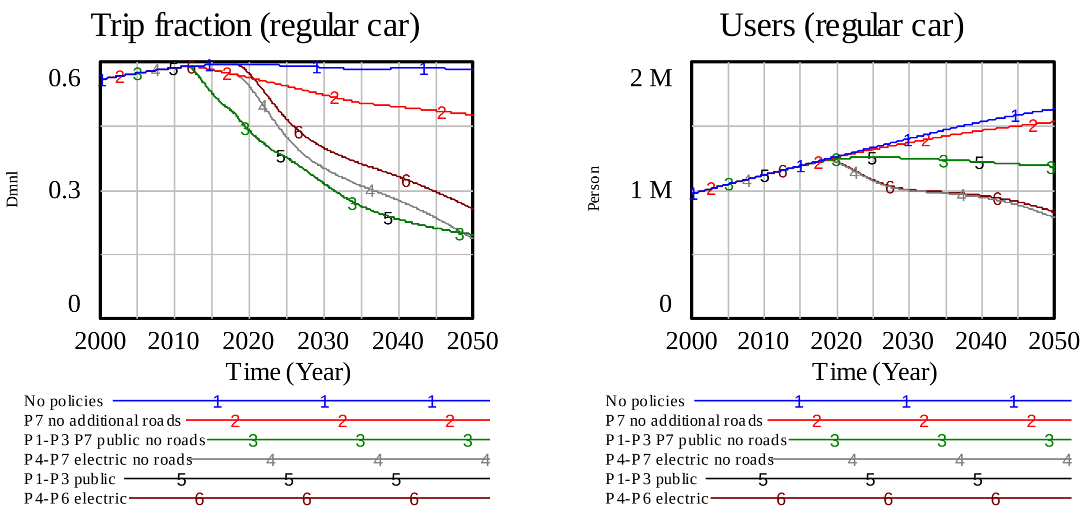


Figure 13 Effect of road building limitations on regular car use

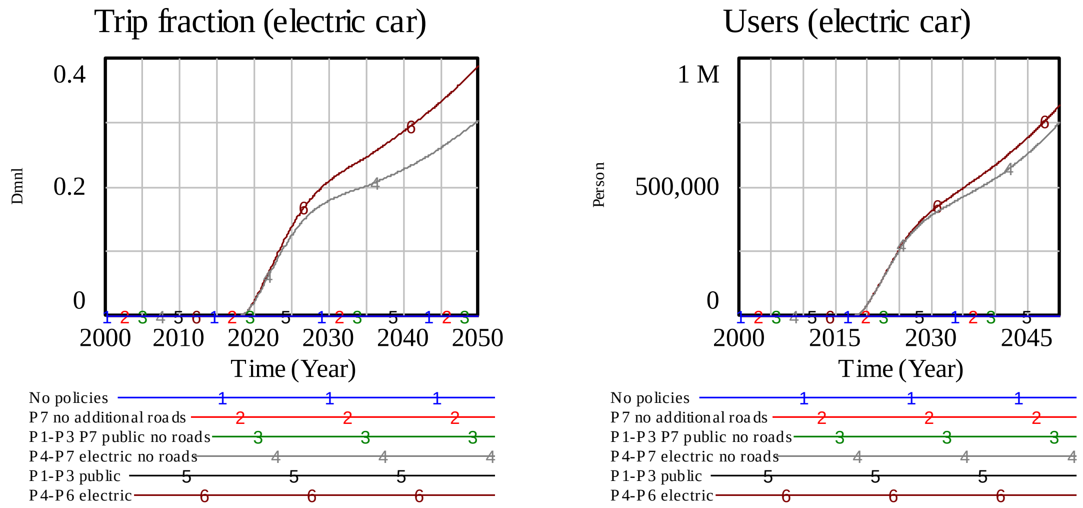


Figure 14 Effect of road building on electric car use

Discussion

The simulation results show that policies affecting the relative attractiveness of the transport modes have a faster effect on the trip fraction than on the number of users. This seems natural since the number of users only changes through car purchases and discards, while the number of trips can be affected by short term considerations. The simulations suggest that policies targeting the adoption of electric vehicle or biofuels can also decrease the trip fraction by public transport. In the model we have assumed that the number of trips by person per day stays constant, but making private car use more attractive can additionally increase the number of trips by car (c.f. Sterman 2000, Ch. 5).

A lesson from the modelling process is that maximisation of public transport usage should be addressed first rather than focusing on the shift from fossil fuels to use of electricity and biofuels in private cars. Promotion of public transport use and discouraging use and ownership of private cars should be the first objective, as it is the most desirable change. In addition to greenhouse gas reductions, public transport has other benefits to private cars, such as reductions in traffic congestion and increased transport safety.

Combined policy measures targeting public transport can make a big difference in its trip fraction. However, public transport as a stand-alone solution is not enough and has to be combined with electric vehicle and biofuel measures. Only after ensuring maximum use of good quality public transport should the complementing policies address the technological change from regular cars to vehicles using electricity or biofuels. These policies should target private cars as well as vehicles used for public transport. While structuring these policies, it is of upmost importance to see to (1) that undesired shift from users of public transport to owners of private cars does not place and (2) that it does not discourage private car owners to change their transport behaviour so that trips previously done by public transport are then done using private car.

Measures that lead to an increase in fraction of trips or number of users in public transport always contribute towards the vision of emission free transport. A shift from private car use (whether from regular cars using conventional or biofuels or from electric vehicles) to public transport is always desired. Also, measures that lead to a decrease in fraction of trips or number of users of regular cars always contribute towards the vision. A shift away from use of conventional fuels is always desired. However, measures that lead to an increase in fraction of trips or number of users in either electric vehicles or biofuels are more complex. If the fraction of trips or number of users of regular cars does also increase, the measure is a failure. The essential thing is to point out the transport choices and user groups that are affected. A shift from public transport to either electric vehicles or cars using biofuels is not desired.

The timing and scheduling of measures is also essential. Because of long construction delays, infrastructure investments have to be started early. Governance measures also set the foundations for the development of the transport system. On the other hand, awareness raising can be started later.

Conclusions

Earlier research has examined the effects of different technologies to help reduce greenhouse gas emissions in transport. While we feel that new technologies are important, public transport also has a significant role in reaching the vision of emission free transport. The novelty of our simulation model is that it includes both aspects in parallel. A broad model boundary necessarily restricts the level of detail, but this was a conscious choice.

There are a number of limitations in the current simulation model. First, the results should be understood as rough and indicative and would benefit from a better coverage of background data and statistics. Second, widening the scope of the model might reveal other unintended consequences. For example, cheap public transportation tickets might not attract car users but rather people who used to travel by bicycle or by foot. Third, the form of electricity or biofuel production was currently not considered. In reality, the form of production affects whether the electricity or biofuel used in vehicles can be considered sustainable.

A benefit of simulation is that the interaction of various change processes can be examined. Here, the simulations helped understand the potential and limits of specific policies. In terms of the policy measures, the simulations showed the benefits of a comprehensive approach in terms of choice, prioritisation, combining and sequencing. The impact of different policy mixes can be analysed to understand whether the different policies would balance one another or lead to undesired directions. Policies must be designed in unison in a way that they work well together and do not undermine each other’s effects.

To conclude, the modelling process has strengthened the assumption that simple measures designed to mitigate complex transport problems are rarely able to do so. Rather, a group of complimentary measures and coordinated action is required. Through combination of individual policy measures, both the effectiveness and tolerability of political interventions can be maximised in the transport system and a higher performance against the objectives can be gained.

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