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Risk and irreversibility of transport interventions

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ABSTRACT

Infrastructure decisions and transport policies are often based on the notion that all decisions are made at one single point in time, based on full information and an accurate evaluation of the benefits and costs of different alternatives. The reality is very much different, especially in the transport sector, due to the complex and dynamic nature of the transport system and the interplay between the many sub-systems that comprise it. Inherent in such complexities are elements of uncertainty, risk, irreversibility, path dependency and lock-in effects.

This article reviews some of the existing literature on risk and risk management. It argues that one way of better accounting for the above elements associated with risk and uncertainty is to devote efforts at the planning stage to the identification of possible unintended adverse effects, as well as during and after implementation of policy measures or policy packages. While it is imperative to address potential unintended adverse effects ex-ante, it is equally important to monitor policy measure or packages ex-post to identify unintended effects and to evaluate whether the initial objectives are being met. Since circumstances are very likely to change over time and unintended effects can arise, there is a need for flexibility in the design of policy packages to allow as much as possible changes in the package if and when intentions and outcome do not match.

1. Introduction

The transport sector is often characterised as a socio-technical system or as an open complex system. The term socio-technical system is a conceptual reminder that technologies affect and are an effect of their broader infrastructural, organisational, regulatory, and symbolic environments. By open complex system we mean that there are multiple interacting markets, with many types of increasing returns and many positive feedback mechanisms between these markets, with many non-linear relationships and time lags and institutional settings as well as interactions with its surrounding markets and environments. Among the characteristics of such systems are path-dependency and lock-in effects.

Such elements are often weakly understood by public officials and policy makers and there is a need to improve risk assessment, risk valuation and risk management. More generally and broadly, there is a need to change the planning framework and to embrace risk and flexibility as part of the planning process. In addition, there is a parallel need to move away from a 'static thinking', associated with the traditional planning methods, towards methods of dynamic planning where decisions are made continuously and based on steady flow of new information.

From an economic perspective the complexity of the transport system has serious consequences. Most economic thinking uses simplifications and models to understand the world. These models will capture the essence of the process and help us understand it, but in doing so things are left out. This does not need to be a serious issue, but it can be when structural

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changes are underway or we seek radical change in direction. The alternative to this simplification is a set of very complicated dynamic models with many variables and different lags. This in turn might easily become a black box limiting, rather than helping, our understanding of the processes involved (see, for example Key, 2011). In other words, transport systems are difficult to model precisely. This is not only linked to the internal complexity of the system, but also to external factors, such as risk and spillover effects from other markets, and feedback effects.

Governing the transport system also means mediating between various conflicting interests and objectives such as economic development, environmental protection, human health and social equality. Further, it must take into consideration technical innovation, quality standards, habits, standards of living and ideological visions.

Although it is possible to reduce the adverse unintended effects of a policy intervention by adopting integrated policy combinations or 'packages' and through appropriate methodologies, tools and models (see Justen et al. (2014a) and (2014b), it is not possible to fully avoid unintended effects. 'Real world' decision-making is always performed under risk and uncertainty. These risks and uncertainties are due to the complexity of the transport system along with compounding risks and uncertainties concerning technology, markets, political context, socio-demographics and changes in values and preferences. This is even more pronounced in policy packaging where the risk profile of individual measures may be correlated. An example of such package is investment in rail and road infrastructures and land use development (see Herder et al., 2011). However if risks associated with individual measures are uncorrelated, a policy package can prove to act as a safeguard against risks.

The conventional economic approaches fail to adequately address the integration of risk and uncertainty into optimal policy design and cannot easily offer solutions to undesirable situations of deep systemic 'lock-in'.

While transport systems are inherently characterized by significant risks and uncertainties, a variety of *ex-ante* and *ex-post* approaches are available to policy makers that may facilitate the development of effective and efficient policy interventions. *Ex-ante* mitigation of unintended effects favours reversible and flexible options acknowledging that decisions made under risk and uncertainty might lead to unintended effects. Thus, the rationale resonates the need for keeping the option of revising decisions and by incorporating risk management into the planning process (see Sørensen et al., 2014). With availability of information gained from monitoring, it is possible to reduce risk and uncertainty, and necessary adjustments in policy design can be made *ex-post*. The availability of information can also help in early detection of unintended effects and *ex-post* intervention to mitigate the unintended effects. Hence, collection of necessary data is an important part of addressing possible unintended adverse effects ex-post. Expecting unintended effects ex-ante or detecting unintended effects ex-post only leads to improvements if there is flexibility built into the policy processes. It demands rethinking of traditional approaches that assume a deterministic model of the world in which the future is predictable.

Section 2 briefly introduces and defines risk, uncertainty, path dependency, irreversibility and lock-in effect. Economic discipline relies on increasing returns to explain path dependency, irreversibility and lock-in effect. Some of the sources of increasing returns in the transport sector are described in this section. In Section 3 we discuss the integration of risk and uncertainty in the policy design with examples from three important policy areas in an EU or a national context, alternative fuel vehicles, infrastructure investments and environment, followed by a discussion on the implications for policy design and implementations. Section 4 provides a summary and conclusions.

2. On risk, uncertainty, path dependency, irreversibility and lock-in effect

The planning euphoria of the 1960s and 1970s, partly based on a relative stability of underlying systems that allowed for the extrapolation to the future to seem adequate, has been recently challenged and it is now widely acknowledged that risks and uncertainty can never be fully avoided. Many authors have raised concern that planning processes in general, and in transport planning in particular, do not adequately address risks and uncertainties (see Gifford 1994; Grunwald 2007). Still, political rhetoric gives the impression that accurate forecasting is possible and uncertainties can be assessed correctly and controlled effectively.

A simple categorisation of the sources of risk and uncertainty can be derived from the Knightian definition of these two terms (Knight 1921).[1] This definition is related to the kind of knowledge that is available in relation to a process or a phenomenon. Risk involves effects for which knowledge and parameters are available in order to assess the likelihood of an outcome; uncertainty refers to a more genuine lack of systematic understanding of causal relations. The inherent complexities of the transport system and its interactions with the surrounding markets and environments, makes it prone to both risk and uncertainty.

Irreversibility, path dependency and lock-in effect are closely related. In economics, path dependency and 'lock in' effects are explained by increasing returns. The central properties of increasing returns are non-predictability, potential inefficiency of outcomes, path dependency and lock-in. We define these concepts in this section. The aim is to emphasise that traditional models in economics are not appropriate for the prediction of outcomes and costs and benefits of a policy intervention when there are associated risk and uncertainty. And it is not easy to escape from a lock-in situation using the *de facto* tax or subsidy policies prescribed by economists.

[1] Different users emphasise different aspects of risks and there are several approaches for a classification of risk and uncertainty.

2.1. Risk and uncertainty

There are many sources of risk and uncertainty in the transport domain, such as those related to stability of preferences over time, technological development and external shocks. Governments can also create uncertainty by generating an expectation of policy change or by not taking a position on an emerging regulatory framework. Policy uncertainty can have significant effect on investment decisions. Hassett and Metcalf (1999) examine the impacts of policy uncertainty on investment decisions using a real option framework and show that these uncertainties reduce irreversible investments.

The uncertainties over costs, benefits, and discount rate have major consequences for the conventional models that assume stability of these parameters over time. The quantitative models that have been addressed in Justen et al. (2014b) are all of this nature. We briefly address risks and uncertainties over benefits, costs and discount rate.

In the rest of the paper risk and uncertainty are used interchangeably.

2.1.1. Risk and uncertainty over benefits, costs and discount rate

Dixit and Pindyck (1994) describe the standard approach to modelling investment under demand uncertainty when investment decisions are partially or totally irreversible. This generates real options on the investment decision and a separation of the thresholds for investment and disinvestment, with no investment undertaken in between these thresholds. Even low levels of uncertainty and irreversibility can lead these thresholds to be significantly spaced apart in relation to their positions under complete certainty and reversibility.

Pindyck (2009) focuses on the uncertainty over the benefits of an environmental policy. The aim of a carbon tax is to result in benefits and that benefits should be larger than the costs of the policy. The timing and the intensity of the policy depend on the specific benefit functions; that is, on how the benefits from the tax vary with its size. The answers also depend on the nature and extent of uncertainty over those benefits.[2] There are other policies, especially with impacts over long time horizons, with uncertainties over the benefit function (and the cost function) and hence the timing and the intensity of the policy should be treated in a similar manner to an environmental policy.

An investment problem faces two types of uncertainty over its cost. One is referred to as 'technical uncertainty' and it is connected to physical difficulty of finishing a project. Technical uncertainty can only be fully resolved by carrying out the project in order to get information about the uncertainties. The second type is referred to as input cost uncertainty and it relates to fluctuations in the price of labour and material and other inputs as well as regulatory regimes that are external to the project. Input uncertainty can be important for projects that take time to complete and can potentially make investment less attractive to be undertaken now. For most policies, particularly those with more limited time horizons, costs are better understood and subject to less uncertainty than are the benefits. Cost functions can also exhibit non-linearity. There are, however, other problems in some policy areas, those with long time horizons, especially related to environmental problems that entail serious cost uncertainty.[3]

Discount rates are a weak or an insignificant determinant of investment demand within conventional economic frameworks. A reduction in the discount rate makes the future more important relative to the present. This increases the value of investing (the expected present value of the stream of benefits) and the value of waiting (the ability to reduce the prospects of future losses). The net effect is weak and even ambiguous. However, uncertainty about the future path of the discount rate can be more crucial for investment than the level of discount rate (see Dixit and Pindyck, 1994).

Risk and uncertainty over discount rates has impact on the choice of the effective rate. Recent studies show that discount rate uncertainty reduces the effective discount rate that should be used for policy evaluation (see Pindyck, 2009). While these studies do not provide a clear answer, they show that the correct rate should decline over a given time horizon and that the rate for the distant future is most likely well below the rates often used for transport and environmental cost-benefit analysis. Thus, costly environmental policies with benefits long from now may indeed be justifiable.

2.2. Irreversibility

There is a large and mounting body of literature that explores the implications of irreversibility. The key concern is the extent to which irreversibility matters *per se* and what implications irreversibility has for the design of policy interventions (Pindyck, 2007).

The literature offers different interpretations of irreversibility. One interpretation is when return to the status quo is impossible or extremely difficult, at least on an appropriate timescale. An alternative interpretation sees irreversibility in terms of sunk cost, corresponding to the definition in economic literature on options (see Sunstein, 2008).

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[2] Pindyckalso points out the possibility of a tipping point in the benefit function, a point after which adaptation does not work, and there are uncertainties associated with the tipping point.

[3] Pindyck (2009) uses global warming and points out to the difficulties in determining the size of the carbon tax for the reduction of the emissions to a target level. The tax-induced price change has different impacts on demand for fossil fuel in different sectors (e.g., transportation versus other sectors). The effect of price change on fossil fuel demand in any sector in turn depends on the long-run price elasticity of energy demand in the sector, and the long-run elasticity of substitution between fossil and non-fossil energy sources. However the long-run elasticity of substitution between fossil and non-fossil energy sources is not known. The ability to substitute depends on the cost and availability of alternatives. The technological changes determine the extent of substitutability over the next twenty or fifty years from now, which is hard to predict at the present time.

For environmentalists, irreversibility is associated with large-scale change in environmental conditions. The relevance of irreversibility lies in its association with damage of extreme magnitude. In real options theory, however, irreversibility is defined in a technical manner. Irreversible investments are sunk costs, those costs that cannot be recovered totally. An example of an expenditure that cannot be recovered is investments in transport infrastructure, which are usually assumed to represent sunk costs. Irreversibility can also arise due to government regulation or institutional arrangements (Dixit and Pindyck, 1994).

There is almost always uncertainty over the future costs and benefits of adopting a particular policy and these can often work in opposite directions (see Sunstein, 2005 and Pindyck, 2009).

With an irreversible investment new information might affect the desirability or timing of the expenditure, and a lost option value is an opportunity cost that must be included as part of the evaluation of the investment. In most cases it is feasible to delay action and wait for new information. With risks, uncertainty and irreversibility, there is almost always leeway about the intensity of the policy and the timing of policy adoption with significant effect on the optimal policy adoption path (see Dixit and Pindyck, 2000; Pindyck, 2009).

2.3. Path dependency and lock-in effect

Dixit and Pyndick (1994, p. 16) define path dependency as a situation where "the current state of the underlying stochastic variable is not enough to determine the outcome in the economy; a longer history is needed. The economy is path dependent." Path-dependency means that the sequence of historical events influences future possibilities (Kaijser, 2005).[4]

The traditional understanding of long run equilibrium paths of development as well as of equilibrium product market development has long been challenged. David (1985), Arthur (1989, 1990) and Leibowitz and Margulis (1995) have provided background by defining and discussing the issue of path dependency and its implications for future actions. They rely on increasing returns to show that there is an array of possible equilibrium solutions to identical economic problems and for that there is a possibility that the prevailed solution to be suboptimal.[5] The prevailing economic outcome in terms of product type, industry, institutions, or location can itself be a product of some inconsequential and random event. Under diminishing returns, static analysis is sufficient; the outcome is unique, insensitive to the order in which choices are made, and to small events that occur during the formation of a market. Under increasing returns a dynamic approach is called for since over time the course becomes less flexible (path-dependent) and eventually leads to the enforcement of a particular structure or lock-in. The dynamics thus take on an evolutionary flavour. Insummary, the properties of increasing returns aremultiple equilibriums, possible inefficiency, lock-inand path-dependence. Arthur (1989) emphasises that it is not possible to predict the outcome from usual knowledge of supply and demand functions and that it is not easy to change from a lock-in by standard tax or subsidy policies.

While most often lock-in effects are discussed in the context of technological change, it has been extended to other situations that exhibit path dependency. Path dependence is a key element in North's (1990) theory of institutional change. According to North, the path of institutional change is shaped by the lock-in that comes from the symbiotic relationship between institutions and the organisations that have evolved as a consequence of the incentive structure provided by those institutions. Path dependencies are related to historical, political and institutional factors that constrain and mediate the choice and implementation of novel control practices. These have been increasingly used as an analytical lens in policy studies. For example, Banister et al. (2011) address the path dependent governance of the transport sector as an obstacle to the implementation of efficient and effective environmental policies in the transport sector.

Exit from an inferior lock-in in an economy depends very much on sources of the self-reinforcing mechanism and on the degree to which the accumulated advantages by the inferior equilibrium are reversible or transferable to an alternative one.

When learning effects and specialised fixed costs are the source of reinforcement, advantages are not usually transferable to an alternative equilibrium, andrepositioning the system is then difficult. Reversing the situation may require substantial subsidy. Capital assets are not easily transferable or reversible.

Exit from lock-in can arise through gradual progress and major innovations, but also through what Gaviria (2001) formulates as a change in 'fundamentals', self-fulfilling prophecies and random mutations.[6] Under all these models that describe exit from lock-in, once the transition gets started, the move to a new equilibrium will happen quickly.

2.4. Sources of increasing returns in the transport sector

We mentioned earlier that the economic discipline relies on increasing returns to explain path dependency and lock-in effect. The most important sources of increasing returns in the transport domain include:

[4] A simple definition provided by one of the referees sees path dependency as: "Once the trajectory is set, it is often difficult to change. In other words, the future might not be an extrapolation from the past, but it has a very strong influence on it."

[5] The literature on increasing returns and positive feedback dates back to 1920s and 1930s. Self reinforcement in this literature goes under different labels; increasing returns, cumulative causation, virtuous, vicious cycle, threshold effect and non-convexity.

[6] Changes in fundamentals relate to changes in technology (or preferences) that lead to changes in behaviour. Self-fulfilling prophecies refers to changes in behaviour of people based on their expectations of changes in other people's behaviour. The assumption under random mutations is that people switch to alternative activities every once in a while without apparent reason. If enough individuals switch simultaneously, the current equilibrium may be subverted. This argument applies only to small populations.

Network externality: Results when one consumer's demand for a product or service depends on how many other consumers have access to the service (Katz and Shapiro, 1985). A network with few subscribers has a high average cost and small externalities. With increase in subscribers, the cost declines and the utility of each subscriber increases. The size of a network has to increase so that rising utility comes into balance with declining cost for the market to "take-off" on its own. Government or the producer can intervene (through subsidy or regulation) to allow the size of a network to reach a critical mass for take-off.

Supply externalities: Describe the relationship between the diversity of offered services and the network's size (Tirole, 1998). Basically these are related to the compatibility problem.[7]

Learning-by-doing: The more a technology is adopted, used and known, the more it will be improved. Since producers expect that technology to dominate, through investments they contribute to the improvement of the technology, as in any self-fulfilling expectation process (Rosenberg, 1982; Atkinson and Stiglitz, 1969).

Economies of scale: As output increases, fixed costs are shared by a larger number of units, resulting in decrease of the average cost. There are other causes of increasing returns to scale as well, such as organisational elements, since specialisation, reengineering of production processes and the use of sophisticated means of financing are not feasible beyond a minimum size of production. The crucial result of economies of scale is that marginal cost is always lower than the average cost.

Increasing returns to information: The more a technology is used, the better it is known and uncertainty is reduced in favour of the dominant technology. Most often the risk involved by R&D expenditures to bring incremental innovations to an existing technology is lower than the risk involved in the development of a new and unknown technology. Risk aversion under these conditions further induces a firm to seek short term financial performance. This leads firms to undertake projects resting upon less risky techniques.

Examples of some of these externalities are illustrated in the example of path dependency in the car system.

2.4.1. Path dependency: the example of the "car system"

There are many positive feedbacks that have determined the co-evolutionary interdependence between the car and its supporting infrastructures. The recognition of the complexity of the system is important for many transport policies. The massive use of motor vehicles has shaped, directed and augmented the structural transformation of urban areas and regionsand in turn these structureshaveguaranteed their dependence on car. While there are differences and particularities in the history of thedependence on car internationally, some generalities apply.

– Car has remained the most important durable goods in the economy.
– The early establishment of the used car market was necessary for the promotion of cars as durable goods and crucial for the expansion of the car market.
– Car industries are characterised by economies of scale and scope.
– The car market has created different networks that are essential for its existence. Network economics characterises many part of the car system.[8]
– Co-evolutionary development of bureaucracies and institutions with the development of the car system that has enhanced the path dependencies.

The development of this path-dependent system can be viewed in the context of increasing returns—such as network externalities encompassing several interrelated networks, supply externalities, learning-by-doing, economies of scale, increasing returns to information, and technological linkages, each with its own dynamics and critical mass that have created a path-dependent system, enhanced by path dependent institutions and governance.

3. Integration of risk and uncertainty in policy design (ex-ante)

Transport economics has extensively studied impacts of policy interventions, such as changes in supply of or demand for transport services (see for example Small and Verhoef, 2007). Numerous economic assessments of transport policy interventions and their likely effects often focus on theoretically optimal solutions. However, it is recognised that due to risk and uncertainty and irreversibility, it is not always possible to completely predict target group responses with conventional economic models.

To varying degrees, most policies share three important characteristics: (i) they are partially or completely *irreversible*, (ii) there is *uncertainty* over the future benefits of the policy and (iii) there is flexibility about the *timing* of project (Dixit and Pindyck, 1994). The traditional theory for the evaluation of policies does not recognise the important quantitative and qualitative interaction between uncertainty and irreversibility and timing. Policy evaluation boils down to deciding whether the benefits of a policy are larger than the costs. The problem is in reality more complicated, especially when costs and benefits of a policy occur over long time horizons and due to risk, uncertainty and irreversibilities. Most investments and environmental policies are in this category.

[7] An example of supply externality is the car market, where variety of products and prices meet the demand of almost all in the car market.

[8] The most obvious of these are the different levels of road networks that have been designed, regulated and operated around the dimension and performance of present car technologies. These road networks literally define patterns of accessibility. The filling stations, repair shops and dealers for the sales of new and used cars are other examples of these networks.

There is a vast literature that deals with methodologies and approaches to planning under risk and uncertainty. OPTIC (2010) and Justen et al. (2014b) covers some of these methodologies and approaches. One approach is the use of option theory. When there is uncertainty about the timing and likelihood of an irreversible loss, one should be willing to pay a sum—the option value—in order to maintain flexibility for the future. The option might not be exercised if it turns out that the loss is not a crucial one. But if the option is purchased, policy makers will be in a position to prevent the loss if it turns out to be large. Alternatively, they might obtain the right to scale back a project, to abandon it, to expand it, or to extend its life. It has wide application to the policy problems associated with risk, uncertainty and irreversibility. There are numerous examples of the application of options theory in the literature in the context of 'long-term effects' (see for example Dixit and Pindyck, 2000 and Gollier et al., 2000). Also the area of technology adoption under uncertainty and irreversibility has received ample attention (see for example Fudenberg and Tirole, 1985). So has the problem of infrastructure investment under demand uncertainty and land allocation problem with economic and environmental uncertainty.

In the following sections we provide examples of three important policy areas in the EU and national contexts where policy packages are introduced under risk and uncertainty and with likelihood of irreversibility. These are: alternative fuel vehicles, infrastructure investment, and environmental problems.

3.1. Alternative fuel vehicle technologies (AFV)

The creation of a self-sustaining market for AFV is very costly for society. It involves consumers, many industries, institutions and considerable investments including those related to the supporting infrastructures. The different stakeholders in these different interacting markets face decisions under uncertainty, including in their relation to governments' policies. "Irreversibility" is considerable in this process. Examples of these policies are taxations, subsidies and regulatory measures related to fossil fuels and alternative fuel vehicles as well as policies related to the supporting infrastructures and industries. The government needs to make the "right" choice among technologies and like other stakeholders face uncertainties and risks. What are the "correct" sets of policies and how should the policies be phased in and out? How should the government address the choice among technologies and what are the variables/factors that need to be taken into consideration for decision making?[9] While a government faces uncertainty in the adoption of an "optimal" policy path, it can create uncertainty by generating an expectation of policy change or by not taking a position at the right time on a necessary regulatory framework. Policy uncertainty can have significant effects on the decisions of many other actors (OECD/IEA, 2007).

Environmental concerns are both local and global and the alternative fuel technologies need to respond to both. The adverse environmental impacts of production and use of alternative fuels, locally and globally, in a life cycle perspective could be larger than that of conventional fossil fuel technologies.

In a recent document IEA (2012) outlines a policy package for improving the fuel economy of road vehicles. The policy package that is recommended is technology neutral. The document points to market failure and uncertainties in the road vehicles market and proposes a policy package comprising of information measures, vehicle fuel economy standards and fiscal measures such as vehicle tax incentives, fuel taxes and user charges. The timing of the implementation of these policies differs and the document recommends monitoring, evaluation of the effectiveness of the policies and revision of policy mix when necessary.

In Sweden a policy package including regulatory measures for the provision of refueling station for ethanol fuel (E85), tax exemption on biofuels, CO_2 tax on fossil fuels, provision of subsidies for the purchase of alternative fuel cars and tax rebate for the purchase of alternative fuel company cars led to the take-off of sales of flexible fuel vehicles and use of E85 by 2005 (see Ramjerdi et al., 2009). The policy package at the national level was enhanced by local policies related to parking and exemption from congestion pricing in Stockholm. Sweden heavily subsidized the stimulation of large "flexible-fuel" passenger cars. With the spike in price of ethanol in 2008 and despite the tax exemption, it was more expensive to drive a flexible fuel car on E85 than on gasoline. The result was a car fleet with a larger CO_2 emission than if the policy package had supported smaller and more fuel efficient cars.[10] The revision of many of these policies has made the policy package more technology neutral. The number of flexible-fuel cars in the Swedish car fleet has now decreased since its peak in 2009.

In Norway the policy package for improving the fuel economy of road vehicles comprises of differential taxation on car ownership and fuels based on CO_2 emissions. An unintended consequence of this package was a large increase of the share of diesel engines in the car fleet resulting in emission of other pollutants, notably particulates and NO_x, harmful for local environments. The policy package is now modified to address this unintended consequence, and there has been a substantial decrease in the sale of diesel fuel cars. The policy package now includes the exemption of electric vehicles from purchase tax.[11] At the local level, parking policies, permission to drive on dedicated bus lanes, exemption from toll payment and provision of recharging stations (on street and in parking lots) has significantly increased the purchase of electric vehicle in many cities in Norway, particularly in Oslo. Obviously, these policies have to be modified over time with the take-off of electric vehicles and increase in the share of electric vehicles in the car fleet.[12]

[9] See for example, Ramjerdi et al. (2009) and Greaker and Heggedal (2010) on the role of governments in technology selection.

[10] See Justen et al. (2014b) for a discussion and a typology of unintended effects.

[11] The exemption does not extend to plug-in electric vehicles.

[12] Electric car technology has changed significantly in the past decade and is expected to change further. The rapid change results in risk and uncertainty both for consumers and producers. With maturity in technology and increase in sales, the price of electric car will decrease and hence reduce the need for purchase subsidies and revision of other policies in the policy package for promoting clean fuel car fleet.

'Getting prices right' in the sense of choosing the desired (socially optimal) path, or scenario, and driving markets along a dynamic pattern of feasible technological change through externality taxation (or emissions permit quota) may not be an easy programme. A single price on greenhouse gas emissions, or subsidy on greenhouse gas abatement, might not discriminate effectively between different technologies that take differing roles into account at different stages in the policy scenario. Arthur (1990) points out to the difficulties of such policy formulation.

3.2. Infrastructure investment

Uncertainties and risks associated with an infrastructure investment problem are numerous, characterised by multiple interactions and with broad consequences for environments and societies. There is an increasing recognition that the scope of project evaluation should be extended to account for uncertainty, irreversibility, and path dependency—in particular in response to the challenges of sustainable development. While transport is a key to economic development, it also contributes a range of societal and environmental costs.

Urban areas and regions are complex systems and provisions of transport infrastructure in such a complex environment have many rebound effects that are long lasting and reinforce the "lock-in" effect. A move to another equilibrium that is potentially more efficient than the present might require substantial effort. As an example public transport and the private car are substitutes to a degree. Each mode is self reinforcing in that the more it is used the more funds become available for investment and improvements that attracts even further users. Then one mode may achieve dominance at the expense of the other. Changing the situation may require substantial subsidy and capital investments (see Arthur, 1990).

Another important setting that reinforces path dependency of the road system is caused by the extent of the development of the road network compared with rail network. This situation favours the extension of the road network compared with the rail network. The extension of the road network most often seems marginal and often the projects can be completed within relatively short time. Thus, the extension of road network almost always compares favourably with rail and even with the additional hurdles of the requirements in real options frameworks. Extensive subsidies to the alternative mode might in fact be desirable in the long run.

Flyvbjerg (2009) examines about 260 major infrastructure projects and draws on three main explanations to account for cost overruns and benefit shortfalls in major infrastructure projects: technical, psychological, and political-economic. Technical explanations relate to imperfect forecasting techniques, inadequate data, and inherent problems in predicting the future. Psychological explanation isrelated to 'optimism bias' – the differences between subjective and objective evaluations of risk and uncertainty by decision makers (see Kahneman and Tversky, 1979and Lovallo and Kahneman, 2003). And political-economic explanations relate to deliberate and strategic overestimation of benefits and underestimating costof projects. Strategic misrepresentation can be traced to agency problems and political and organisational pressures—for instance, competition for scarce funds.

Strand and Miller (2010) address the options of scaling down energy consumption and carbon emissions in the future and the costs of these policies. They focus on bulky infrastructure investments, such as investment on road infrastructure, sunk at an initial time of decision, that 'tie up' energy consumption for a long future period and make it more costly to reduce emissions later. With expected energy and environmental costs continually on the rise, inherent biases in the selection processes for infrastructure investments lead to excessive energy intensity in such investments.[13] The potential reasons for bias include: systematic under-valuation of future energy costs; failures to incorporate true (current and future) social carbon emissions costs; and excessive discounting. It is increasingly recognised that the presence of such an established infrastructure may form a major *ex-post* obstacle to effective mitigation policy. This is the case regardless of whether the *ex-ante* infrastructure investment is 'optimal' or not.

Infrastructure investmentpolicies are often part of a policy package that includes land use policies. Herder et al. (2011) examine the use of option theory for the valuation of infrastructure projects in different sectors (transport and land use, port infrastructure and energy infrastructure). They provide an example of a policy package comprising investments in rail and road infrastructures and land use development. They point out that these type of projects are irreversible once implemented and implementation takes a long time. The uncertainties in this context are many, related to economic fluctuations, technological changes, changes in stakeholders and political shifts. They also point out that these uncertainties have only increased recently, making decisions even more risky. They identify several reasons for not applying option theory in particular for the evaluation of infrastructure and land use projects. These are related to several problems of capacity, of decisiveness, of lock-in, of compound uncertainty and of applicability. They suggest that the most pertinent problem among these is the problem of lock-in, related to the political setting, the institutional setting, and the organisational inflexibility.

3.3. Environmental policies

Uncertainties are large for many environmental problems. Hence, consideration of uncertainty is more important and relevant for policy design and evaluation concerned with the environment. Pindyck (2007) addresses three key complications that are often crucial to environmental policy. These are first that environmental cost and benefit functions tend to be *highly*

[13] See also Brueckner (2000) and Glaeser and Kahn (2008) for the effects of infrastructure choice on energy consumption and CO_2 emissions.

nonlinear. The second is that environmental policies usually involve important *irreversibilities*, and those irreversibilities sometimes interact in a complicated way with uncertainty. The irreversibilities of environmental policies work in opposite directions. Policies aimed at reducing environmental degradation almost always impose sunk costs on society. If future costs and benefits of the policy are uncertain, these sunk costs create an opportunity cost of adopting the policy, rather than waiting for more information about environmental impacts and their economic consequences. This implies that traditional cost-benefit analysis will be biased *toward* policy adoption. On the other hand, environmental damage is often partly or totally irreversible. This means that adopting a policy now rather than waiting has a negative opportunity cost. This implies that traditional cost-benefit analysis will be biased *against* policy adoption. The third complication is that, unlike most capital investment projects and most other public policy problems, environmental policies often involve *very long time horizons*, especially the benefits from an environmental policy can extend for a hundred years or more. The problem of climate change is a well known example with long time horizons, but there are also others. The uncertainty regarding costs and benefits of policies increases with the time horizon. A long time horizon also makes discount rate uncertainty much more important.

Uncertainties over benefits and costs can affect policy design in at least three fundamental ways. First, they can affect the optimal choice of *policy instrument* that is whether pollution is best controlled through a price-based instrument (e.g., an emissions tax) or a quantity-based instrument (e.g. emission quota). Second, they can affect the optimal *policy intensity*, for example, the optimal magnitude of the tax or the optimal level of abatement. Third, they can affect the optimal *timing of policy implementation* that is whether it is best to put an emissions tax in place now or wait several years and thereby reduce some of the uncertainty (see Pindyck, 2007).

The consequence of uncertainty for the optimal choice of policy instruments (a policy package) has been studied extensively, beginning with the seminal work by Weitzman (1974), who showed that in the presence of cost uncertainty, the relative slopes of the marginal benefit function and marginal cost function determine the choice of instrument; a price-based or a quantity-based. In a world of certainty, either instrument will be equally effective. If there is substantial uncertainty and the slopes of the marginal benefit and cost functions differ considerably, the choice of instrument can be crucial.[14] Uncertainties and lack of knowledge of the shapes of the benefit and cost functions means that policy design will be suboptimal at best. With availability of information, it is possible to adjust the policy mix over time.

3.4. Implications for policy design and implementation

Policy adoption is rarely a now ornever proposition. With uncertainty and irreversibility associated with policy intervention, it might be desirable to delay action and wait for new information. With uncertainties and irreversibility, there is a leeway about the intensity of the policy and the timing of policy adoption with significant effect on the optimal policy adoption path. Option theory provides support for decisions under such circumstances.

How important are these irreversibilities and what are their implications for policy? The answers depend on the nature and extent of the uncertainties over costs and benefits, and how those uncertainties are likely to get resolved over time. The compounding set of risk and uncertainties in the policy arena implies that policies and invest ment decisions are based on imperfect and incomplete knowledge. While ex-ante integration of risk and uncertainty in the designs of policy interventions is important, it is equally important to collect the necessary information to intervene ex-post for the necessary policy adjustments.

If decision parameters cannot be observed and measured, there is a demand for rethinking traditional approaches that assume a deterministic model of the world in which the future is predictable (Lewis, 2007, cited in World Bank, 2009). But the required structural changes can be dif ficult because of the inertia in the established management practices (see for example Folke et al., 2002).

4. Summary and conclusions

Policymakers in the transport sector are often required to make decisions in the face of risk and uncertainty. Most evidently, this stems from a lack of information concerning a particular transport problem, the inability of existing modelling tools to accurately encompass the range of variables and causal relationships involved and the messy, intractable nature of the policy process itself. Risks and uncertainties are particularly pertinent to the context of policy making at a national as well as an EU level, where an extraordinarily diverse array of technologies, markets and political, institutional and socioeconomic contexts are present. We have reiterated throughout this paper that contemporary European transport systems may thus be considered to represent complex socio-technical systems, prone to conditions of path-dependency and lock-in effects.

Overall, this paper concludes that contemporary transport systems are inherently characterised by significant risks and uncertainties. The core consideration that emerges from this work is the importance of adaptive and flexible policy-making. Indeed, without such flexibility, ex-post activities such as monitoring or remedial action simply become worthless and obsolete, respectively. As noted, coping with complexities plays a crucial role in planning process; the more complex a system, the greater is its associated uncertainties, and thus the greater need for flexibility to be embedded in the design of policy

[14] Weitzman's original result has been extended in a number of directions (see for example Stavins, 1996; Jacoby and Ellerman, 2004).

measures. Flexibility is thus important in the context of policy intervention irreversibility (e.g. investment in infrastructure) or irreversibility associated with the problem that the policy package itself aims to mitigate (e.g. anthropogenic climate change).

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