To drive or not to drive? A simple evolutionary model

Antoci, Angelo and Borghesi, Simone and Marletto, Gerardo

University of Sassari, Italy, University of Siena, Italy, University of Sassari, Italy

2012

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Angelo Antoci (University of Sassari)*

Simone Borghesi (University of Siena)

Gerardo Marletto (University of Sassari)

Abstract

Car use is an increasingly serious problem in many modern cities because of polluting emissions, noise, accidents and congestion. To examine this issue, this paper analyzes the individual choice between taking the car and using alternative transport modes (e.g. walking, cycling, taking the bus etc...) in the presence of cars' negative impacts on alternative transport modes. Using a simple evolutionary model, we show the existence of suboptimal Nash equilibria characterized by the widespread use of cars and discuss the effects of simple transport policies that reduce cars' negative impacts on alternative transport modes.

Keywords: urban transport; cars; negative impacts; evolutionary dynamics; suboptimal Nash equilibria

JEL classification: C73, D62, R40, R41

* Corresponding Author: Angelo Antoci, Department of Economics, University of Sassari, Via Torre Tonda 34, 07100 Sassari, Italy, email: antoci@uniss.it

1. Introduction

The current unsustainability of urban activities largely depends on the use of the car as the prevailing transport mode. As is well known, the extensive car use that characterizes modern cities all over the world generates several negative effects on the welfare of the population. In the first place, cars are a significant contributor to the emission of some health-damaging air pollutants in cities, such as: fine and coarse particulates (PMx), nitrogen oxides (NOx), ozone (O_3) and benzene. Ambient air pollution has been associated with increases in mortality and morbility in many European urban studies (EEA, 2010a). The World Health Organization estimates that PMx generated by urban transport accounts for 36,000-129,000 adults death a year in European cities; as a result, life expectancy is shortened by an average of a year (Dora and Phillips, 2000). In the second place, car use generates accidents: in the European Union more than 40,000 people are killed and more than 150,000 are disabled for life by road crashes – almost half of these events take place in urban areas (WHO, 2004). Jacobs et al. (2000) estimated that roads crashes and injuries cost high-income countries an average 2% of their GNP: both direct costs (health care, rehabilitation, property damage, etc.) and indirect costs (lost household services and lost earnings) are considered. In the third place, car use is associated with noise (EEA, 2010a): transport noise disturbs and interferes with concentration and activities such as communication, relaxation and sleep; in addition, there are concerns about direct health impacts including effects on the cognitive development of children, endocrine balance, and cardiovascular disorders. At night, almost 40 milion people (living in European agglomeration with more than 250,000 inhabitants) are exposed to an average road noise levels exceeding 50 dB, a level at which adverse health effects become measurable. All the above negative impacts of car use are decreasing or will decrease: between 1990 and 2007 most air pollutants registered a significant reduction (EEA, 2010b); since the 1960s and 1970s both road traffic death rates and absolute values have decreased; the dramatic felling of road noise is one of the expected otucome of the electric car. But there is one negative impact of car use which is continuosly increasing: congestion. In 2000 IWW and Infras estimated that additional time costs caused by road congestion amount to 1,9% of the European GDP (70-80% of which results from urban traffic). The increasing traffic congestion deriving from car use is often reported by the individuals as a main cause of chronic stress and unhappiness (Stutzer and Frey, 2008). Several studies (e.g. Kim, 2008; Kirby and Le Sage, 2009) have found that in the last few years the time devoted to commuting has been constantly high or even further rising in most urban areas, while the average speed of cars has become very low in many cities. For instance, as pointed out by a recent study on Italian towns (Anci, 2009), the main Italian city centers show similar low average car speeds, ranging between 22 km/h in Milan and 26 km/h in Turin. Recent studies conducted in the UK have found that in central London the average car speed during rush hours fell from 12.7 miles-per-hour (mph) in 1968 to 8.6 in 2002 (or, equivalently, from around 20 to less than 15 km/h) (Leape, 2006). Similar results emerge also from other studies on inner cities across Europe such as Lyon (Jensen et al. 2010) which reveal that urban cyclists can actually outstrip the average car speed during rush hours. This leads to the paradoxical result that some slow transport modes (e.g. cycling or walking) turn out to be faster than cars for short and medium-distance destinations, as it can be easily verified, for instance, by using Google maps or similar services that compare the time needed to go from one place to another within a town with different transport means.

The consequences of car transport and their implications for transport policy are the object of an extensive literature and of a heated debate among scholars (cf., among the others, Nieuwenhuis et al., 2006; Banister, 2008; Bristow et al., 2008; Moriarty and Honnery, 2008; Dennis and Urry, 2009; Kohler et al., 2009; Sperling and Gordon, 2009; Hull, 2011; Kemp et al., 2011) and institutions (e.g. DfT, 2009; EC, 2009 and 2011; EEA, 2010b; The Climate Group, 2011).

The present paper intends to contribute to a deeper understanding of the forces underlying the current extensive car use and its welfare effects, by offering an evolutionary model that: a) explains the modal split of urban mobility in terms of individual choices, and b) explicitly considers the negative effects of the use of the car on users of other modes. It is also assumed that the more the car is used, the more negative effects are generated – in terms of congestion, accidents, pollution and noise – both for car users and for users of alternative transport modes. The evolutionary model proposed here contributes to the increasing strand of the literature that adopts an evolutionary approach to investigate environmental issues[1]. The evolutionary approach has been used to investigate several environmental issues such as: the interaction of cultural and biotic systems (Kallis and Norgaard, 2010), the management of ecosystems and common pool resources (e.g. Dietz et al., 2003; Noailly et al. 2003; Hoekstra and van den Bergh, 2005; Rammel et al., 2007), the design of institutions to foster the transition to environmentally sustainable economies (Becker and Ostrom, 1995; van den Bergh et al., 2007), the link between innovation strategies and environmental regulation (e.g. Oltra and Saint-Jean, 2005; Sartorius, 2006; Dijk et al., 2011), individual behaviour and environmental policies (e.g. van den Bergh et al., 2000). Among the latter set of contributions, in particular, we can distinguish two research lines that are closely related to the present work. On the one hand, a few studies (e.g. Antoci and Bartolini, 2004; Antoci and Borghesi, 2010 and 2012) have used a game theoretical evolutionary framework to show that environmental self-protective choices can generate suboptimal equilibria, leading the economic system along trajectories in which the economy may grow without generating a corresponding welfare growth.[2] On the other hand, some studies have recently used a similar evolutionary context to study the dynamics that may emerge from the implementation of a new financial mechanism for environmental protection originally proposed by Horesh (2002), with particular emphasis to its possible application and effects in the context of city-users (Antoci et al., 2012a,b). The

[1] See van den Bergh, 2007, and Faber and Frenken, 2009, for a review of the applications of evolutionary concepts and models to environmental economics.

[2] By self-protective choices we mean any individual choice and/or expenditure performed by an agent to protect from environmental degradation. See the seminal paper by Leipert (1989) for a classification of the defensive expenditures related to such behaviour.

present paper joints and further enhances these two research lines as it focuses on the behaviour of city users, showing the existence of possible welfare reducing paths that may derive from their interaction.

The proposed model, moreover, contributes to the scarce literature that makes use of an agent-based approach to the analysis of modal choice. As acknowledged by Hollander and Prashker (2006) in a survey of transport studies based on non-cooperative games, only one out of twenty-three models deals with the issue of modal choice (Van Vugt et al., 1995); such a model presents a two-players game where each player chooses either car or public transport and a Nash equilibrium with both players using a car is generated. More recently, Sunityoso and Matsumoto (2009) – starting from a seminal paper on self-reinforcing motorization of Kitamura et al. (1999) – have proposed a model which is able to represent modal choice as the result of an imitative game involving two groups, that is, cooperative bus users and non-cooperative car users; which equilibrium is generated – among the many possible – depends on the social interaction between the two groups of users.

Our model is at the same time simple and general, thus providing an alternative approach to the analysis of the problem with respect to the one prevailing so far in the existing literature. In particular, the model is able to represent the behavior of a whole population of city-users and to generate a numerous set of dynamics, without the need for heterogenous players.

With simple but realistic assumptions the model is able to describe the dynamics that emerge in an evolutionary context and prove the existence of suboptimal Nash equilibria characterized by the widespread use of cars. In particular, when there can simultaneously exist only two pure Nash equilibria in which either everyone takes the car or none does it, then the former is Pareto dominated by the latter. When, on the contrary, alternative transport modes can coexist at the equilibrium, we show that such equilibrium is Pareto dominated by the state in which no city user takes the car. Moreover, the model can easily show how simple transport policy which reduce the negative effects of the car on alternative modes (e.g.

reserved and protected lanes) may lead to equilibria featuring a higher share of buses and bicycles.

The structure of the paper is as follows. Section 2 sets forth the evolutionary model that is investigated in the paper, Section 3 describes the dynamics that emerge from the model, distinguishing between two possible cases according to the relative impact of car use on the alternative transport modes. Section 4 provides a specific example assuming a particular specification of the payoff funcions. Section 5 concludes.

2. The model

In each instant of time *t*, city users have to choose whether to use a private car (choice A) or to use an alternative transport mode (walking, cycling, using buses or trams etc...) (choice B). Let us indicate by $x(t)$ the share of the population of city users adopting choice A at the instant *t*; consequently $1 - x(t)$ represents the share of those choosing B.

We will denote with $\Pi_A(x)$ and $\Pi_B(x)$ the payoff functions of strategies A and B, respectively. The process of adopting strategies A and B is modeled by the so called replicator dynamics (Weibull, 1995), according to which the strategy whose expected payoffs are greater than the average payoff spread within the populations at the expense of the other. In our case, the replicator dynamics can be written as:

$$\dot{x} = x(1 - x)[\Pi_A(x) - \Pi_B(x)] \tag{1}$$

Where $\dot{x}$ is the time derivative of *x*(*t*). Notice that the pure population states $x = 1$ (all individuals adopt strategy A) and $x = 0$ (all individuals adopt strategy B) are always stationary states of dynamics (1) (that is $\dot{x} = 0$ if $x = 1$ or $x = 0$). A mixed population state $\bar{x} \in (0,1)$ is a stationary state of (1) if and only if $\Pi_A(\bar{x}) = \Pi_B(\bar{x})$, that is if the payoffs of the two available strategies, evaluated at $\bar{x}$, are equal and consequently no individual is motivated to revise his strategy choice.

We make the following assumptions about the derivatives of $\Pi_A(x)$ and $\Pi_B(x)$: $\Pi'_A(x) < 0$ and $\Pi'_B(x) \leq 0$; that is, when x increases, the payoff of A strictly decreases while that of B may strictly decrease or remain constant. In this context, we will distinguish between two possible cases depending on whether $\Pi_A(x)$ decreases less or more rapidly than $\Pi_B(x)$. The former is characterized by the fact that the diffusion of the strategy A (to use the car) in the population of city users produces negative effects which are higher for individuals choosing strategy B rather than for those adopting strategy A. The opposite holds in the latter context.

3. Evolutionary dynamics

3.1. Scenario 1: $0 > \Pi'_A(x) > \Pi'_B(x)$ (an increase in *x* negatively affects individuals choosing strategy A less than those adopting strategy B).

In this context, the payoff difference $\Pi_A(x) - \Pi_B(x)$ is a strictly increasing function of the share x (being $\Pi'_A(x) - \Pi'_B(x) > 0$ always); that is, the relative performance of strategy A, with respect to strategy B, increases when x increases. We can distinguish three possible sub-cases, according to the relative position of the curves $\Pi_A(x)$ and $\Pi_B(x)$ in the (x, Π) plane (see Figures 1-3). In particular, the dynamic regimes under equation (1) can be classified as follows:[3]

Proposition 1. *In the context* $0 > \Pi'_A(x) > \Pi'_B(x)$, *the taxonomy of the dynamic regimes exhibited by equation (1) is:*

a) *If* $\Pi_A(0) \geq \Pi_B(0)$ *(i.e. the graph of* $\Pi_A(x)$ *always lies above that of* $\Pi_B(x)$*), then whatever is the initial distribution* $x(0) \in (0,1)$ *of strategies, the trajectory*

[3] The proofs of the following propositions are straightforward, so we shall omit them.

starting from $x(0)$ approaches the stationary state $x = 1$, where all individuals adopt strategy A (see Figure 1).[4]

b) *If $\Pi_A(1) \leq \Pi_B(1)$ (i.e. the graph of $\Pi_A(x)$ always lies below that of $\Pi_B(x)$), then whatever is the initial distribution $x(0) \in (0,1)$ of strategies, the trajectory starting from $x(0)$ approaches the stationary state $x = 0$, where all individuals adopt strategy B (see Figure 2).*

c) *If $\Pi_A(0) < \Pi_B(0)$ and $\Pi_A(1) > \Pi_B(1)$ (i.e. the graphs of $\Pi_A(x)$ and $\Pi_B(x)$ cross in the (x, Π) plane), then there exists a mixed population stationary state $x = \bar{x} \in (0,1)$, which is repulsive. Whatever is the initial distribution $x(0) > \bar{x}$ of strategies, the trajectory starting from $x(0)$ approaches the stationary state $x = 1$ while whatever is the initial distribution $x(0) < \bar{x}$ of strategies, the trajectory starting from $x(0)$ approaches the stationary state $x = 0$* (see Figure 3).

Insert Figures 1-3 about here

The above proposition shows that, in the context $0 > \Pi'_A(x) > \Pi'_B(x)$, the adoption process of choices A and B is self-enforcing and only pure population attractive stationary states (which are, in such case, Nash equilibria) can exist where either $x = 1$ (all individuals choose A) or $x = 0$ (all individuals choose B). In case (c) of the proposition, the dynamics is path-dependent in that the final outcome ($x = 0$ or $x = 1$) is determined by the initial distribution $x(0)$ of strategies. This means that if a sufficiently high number of agents chooses to use the car ($x(0) > \bar{x}$), then also the others will make the same choice, so that at the end of the day everyone uses the car ($x = 1$). Similarly, if a sufficient number of agents decides not to use

[4] Notice that $\Pi_A(x)$ and $\Pi_B(x)$ have been represented as concave functions in the figures, so that the agents' payoffs diminishes at an increasing rate as x increases. The classification of the possible cases described above, however, depends only on the relative positions of the graphs of $\Pi_A(x)$ and $\Pi_B(x)$ and is independent of their shape as long as the payoffs difference $\Pi_A(x) - \Pi_B(x)$ is a monotonic function of x.

the car (i.e. their share x is initially below the threshold level $\bar{x}$), this strategy will spread across the population so that none uses the car at the equilibrium ($x = 0$). The attractive stationary states $x = 0$ and $x = 1$ can, therefore, be interpreted as stable social conventions in which all agents make homogeneous choices and a unique strategy prevails in the population.

Notice that the population average payoff is given by:

$$\overline{\Pi}(x) := x\Pi_A(x) + (1 - x)\Pi_B(x)$$

So $\overline{\Pi}(1) = \Pi_A(1)$ and $\overline{\Pi}(0) = \Pi_B(0)$. As Figures 2 and 3 show, in the cases (ii) and (iii) of the Proposition 1, $\Pi_B(0) > \Pi_A(1)$ always holds. In other words, the agents are always better-off if they all choose strategy B (i.e. they do not use the car) rather than if they all choose A. However, if the curves cross (Figure 3), the dynamics of the model may lead the agents to adopt the strategy A that will make everyone worse-off. In fact, if the initial share x_0 is above the threshold level $\bar{x}$, the strategy A is individually perceived as the best strategy in response to the others' choices (i.e. $\Pi_A(x) > \Pi_B(x)$ for every $x_0 > \bar{x}$). As the use of cars spreads among the population, however, the whole community ends up on a socially undesirable outcome since the agents' welfare in $x = 1$ is lower than in $x = 0$. In this case, the choice of strategy A gives origin to an undesirable social convention that represents a stable Nash equilibrium of the economy.

A similar outcome may also occur when the graph of $\Pi_A(x)$ lies always above that of $\Pi_B(x)$ so that everyone wants to move by car (case (a) of Proposition 1). As Figure 1 shows, although $\Pi_A(x) > \Pi_B(x)$ for every x, we can still have $\Pi_B(0) > \Pi_A(1)$. Even in this case, therefore, the strategy selection process may thus lead the agents to choose $x = 1$ although the welfare level in $x = 1$ is lower than in $x = 0$. In this case, differently from the cases (b) and (c) of Proposition 1, the stationary state $x = 0$ is not attractive under evolutionary dynamics (1).

Finally, notice that $\bar{\Pi}(\bar{x}) := \bar{x}\Pi_A(\bar{x}) + (1-\bar{x})\Pi_B(\bar{x}) = \Pi_B(\bar{x})$ holds, being $\Pi_A(\bar{x}) = \Pi_B(\bar{x})$, in the context (c) of Proposition 1. Since $\Pi_B(0) > \Pi_B(\bar{x})$ (see Figure 3), then the attractive stationary state $x = 0$ also Pareto-dominates the repulsive stationary state $\bar{x}$ where both strategies coexist.

The following proposition sums up the above results on welfare.

Proposition 2. *In the context* $0 > \Pi'_A(x) > \Pi'_B(x)$*, we have that:*

1) *the stationary state* $x = 0$ *always Pareto-dominates the stationary state* $x = 1$, that is $\bar{\Pi}(0) > \bar{\Pi}(1)$*, in sub-cases (b) and (c) of Proposition 1. Furthermore,* $x = 0$ *may also dominate* $x = 1$ *in sub-case (a), that is, even if* $x = 0$ *is not attractive; in particular, this happens when* $\Pi_B(0) > \Pi_A(1)$ *(as in Figure 1).*
2) *The stationary state* $x = 0$ *always Pareto-dominates the stationary state* $\bar{x} \in (0,1)$, that is $\bar{\Pi}(0) > \bar{\Pi}(\bar{x})$.

3.2. Scenario 2: $\Pi'_A(x) < \Pi'_B(x) \leq 0$ (an increase in *x* negatively affects individuals choosing strategy A more than those adopting strategy B).

In this context, the payoff difference $\Pi_A(x) - \Pi_B(x)$ is a strictly decreasing function of the share *x*; that is, the relative performance of strategy A, with respect to strategy B, decreases when *x* increases. As we shall see, this context favors the coexistence between strategies A and B. Like for Scenario 1, even in this case we can distinguish three possible sub-cases according to the relative position of the curves $\Pi_A(x)$ and $\Pi_B(x)$ in the (x, Π) plane, as the following proposition shows (see Figures 4-6).

Proposition 3. *In the context* $\Pi'_A(x) < \Pi'_B(x) \leq 0$*, the taxonomy of the dynamic regimes exhibited by equation (1) is:*

a) *If* $\Pi_A(1) \geq \Pi_B(1)$ *(i.e. the graph of* $\Pi_A(x)$ *always lies above that of* $\Pi_B(x)$), *then whatever is the initial distribution* $x(0) \in (0,1)$ *of strategies, the trajectory starting from* $x(0)$ *approaches the stationary state* $x = 1$*, where all individuals adopt strategy A (see Figure 4).*

b) *If* $\Pi_A(0) \leq \Pi_B(0)$ *(i.e. the graph of* $\Pi_A(x)$ *always lies below that of* $\Pi_B(x)$), *then whatever is the initial distribution* $x(0) \in (0,1)$ *of strategies, the trajectory starting from* $x(0)$ *approaches the stationary state* $x = 0$*, where all individuals adopt strategy B (see Figure 5).*

c) *If* $\Pi_A(0) > \Pi_B(0)$ *and* $\Pi_A(1) < \Pi_B(1)$ *(i.e. the graphs of* $\Pi_A(x)$ *and* $\Pi_B(x)$ *cross in the* (x, Π) *plane), then there exists a mixed population stationary state* $x = \bar{x} \in (0,1)$*, which is globally attractive. Whatever is the initial distribution* $x(0) \in (0,1)$ *of strategies, the trajectory starting from* $x(0)$ *approaches it* (see Figure 6).

Insert Figures 4-6 about here

Notice that in sub-case (c) of Proposition 3, at the stationary state $\bar{x} \in (0,1)$ one can observe heterogeneous choices within the population (some people choose strategy A and others choose strategy B) and the coexistence between these strategies tends to persist over time (the stationary state being attractive).

Notice that, since $\bar{\Pi}(\bar{x}) = \bar{x}\Pi_A(\bar{x}) + (1 - \bar{x})\Pi_B(\bar{x}) = \Pi_B(\bar{x})$ and $\bar{\Pi}(0) = \Pi_B(0)$, in the context (c) of Proposition 3 it holds $\bar{\Pi}(0) \geq \Pi_B(\bar{x})$. Consequently, the repulsive stationary state $x = 0$ Pareto-dominates the attractive stationary state $\bar{x}$ if $\Pi_B(0) > \Pi_B(\bar{x})$ holds (as in Figure 6). In such case, although everyone would be better-off choosing strategy B (i.e. at $x = 0$), the dynamics that emerge from the strategy adoption process leads away from $x = 0$ towards the attractive state $\bar{x}$, so that when $x(0) < \bar{x}$ the community moves along a welfare-reducing path. Notice that $\Pi_B(0) = \Pi_B(\bar{x})$ holds if $\Pi'_B(x) = 0$ for every $x \in (0, \bar{x})$, that is, if the payoff $\Pi_B(x)$ does not depend on the share x in the interval $(0, \bar{x})$.

Welfare properties of attractive stationary in sub-cases (a) and (b) of Proposition 3 can be analyzed following the same steps followed for sub-cases (a) and (b) of Proposition 1. The following proposition sums up the results on welfare in the context $\Pi'_A(x) < \Pi'_B(x) \le 0$.

Proposition 4. *In the context* $\Pi'_A(x) < \Pi'_B(x) \le 0$, *we have that:*

1) *The stationary state* $x = 0$ *always Pareto-dominates the stationary state* $x = 1$, that is $\overline{\Pi}(0) > \overline{\Pi}(1)$, *in sub-cases (b) and (c) of Proposition 3. Furthermore,* $x = 0$ *may also dominate* $x = 1$ *in sub-case (a), in particular, this happens when* $\Pi_B(0) > \Pi_A(1)$ (as in Figure 4).
2) *The stationary state* $x = 0$ *Pareto-dominates the stationary state* $\bar{x} \in (0,1)$, that is $\overline{\Pi}(0) > \overline{\Pi}(\bar{x})$, *if* $\Pi_B(0) > \Pi_B(\bar{x})$, *that is, if the payoff function* $\Pi_B(x)$ *is not constant in the interval* $[0, \bar{x}]$. *A sufficient condition to have* $\Pi_B(0) = \Pi_B(\bar{x})$ *(no Pareto-dominance of* $x = 0$ *over* $\bar{x}$*) is* $\Pi'_B(x) = 0$ *for every* $x \in (0,1)$.

The Proposition above suggests that, if the relative performance of using the car is inversely related to the share of car users, then the society converges towards an equilibrium in which the agents are worse-off than in the case where there are no car users. However, if we could eliminate the negative effects that cars can have on pedestrians, cyclists and other users of alternative transport systems (i.e. if the strategy B is such that $\Pi'_B(x) = 0$ for every $x \in (0,1)$), then individuals would be equally well-off at the attractive stationary state $\bar{x}$ as in the case with no cars around. This can be obtained, for instance, by introducing pedestrians zones or fast lanes specifically devoted to cyclists or buses from which cars are banned, so that the former are not trapped in the traffic jam.[5]

4. A specific example

To fix ideas, in this section we analyze dynamics (1) under a particular specification of the payoff functions $\Pi_A(x)$ and $\Pi_B(x)$, in particular, we pose:

$$\Pi_A(x) = a - bx^2$$

$$\Pi_B(x) = c - dx^2$$

where *a*, *b*, *c*, *d* are parameters of the model.

In this context, the replicator equation (1) becomes:

$$\dot{x} = x(1-x)[\Pi_A(x) - \Pi_B(x)] = x(1-x)\left[a - c - (b-d)x^2\right]$$

Furthermore, we have:

$$\Pi_A(0) = a, \quad \Pi_A(1) = a - b, \qquad \Pi_B(0) = c, \quad \Pi_B(1) = c - d$$

The parameters *a* and *c* measure the net benefit of using the car and the alternative transport modes, respectively, in absence of other car users (i.e. when $x = 0$). The parameters *b* and *d* measure the negative effects generated by the diffusion of choice A in the city users population (e.g. the effects due to traffic congestion, accidents or air pollution), which in this payoffs specification are assumed to increase more than proportionally with the share *x*.

With this payoffs specification, the Scenario 1 (where $0 > \Pi'_A(x) > \Pi'_B(x)$ holds) corresponds to the case $d > b > 0$ while the Scenario 2 (where $\Pi'_A(x) < \Pi'_B(x) \leq 0$ holds)

[5] Notice, however, that fast lanes are not sufficient to avoid the exposure to air pollutants released by cars and the related health-damages that are inevitably suffered by pedestrians, cyclists and those waiting at the bus stop because of the traffic congestion that surrounds them. The absolute value of $\Pi'_B(x)$, therefore, can be substantially reduced by the adoption of fast lanes but is difficult to actually obtain $\Pi'_B(x) = 0$ for every *x*.

corresponds to the case $b > d \geq 0$. In the context $d > b > 0$, the repulsive interior stationary state $\bar{x}$ (see case (c) of Proposition 1) is given by $\bar{x} = \sqrt{\frac{c-a}{d-b}}$. The point $\bar{x}$ separates the basin of attraction $(\bar{x},1]$ of the Pareto-dominated stationary state $x = 1$ from that of the stationary state $x = 0$, $[0,\bar{x})$ (see Figure 3). The next proposition illustrates how the size of these basins of attraction varies according to the variations in the parameters of the model.

Proposition 5. *The size of the basin* $[0,\bar{x})$ *increases (and, consequently, the size of* $(\bar{x},1]$ *decreases) if the values of the parameters b and c increase or if the values of a and d decrease.*

The proof is straightforward.

Stated differently, a decrease in the net benefit *a* of using the car when there are no other cars around and/or an increase in the negative impact *b* of using the car on the other car users tend to reduce the attraction basin of $x = 1$ with respect to that of $x = 0$. This means that a lower initial share of non-car users will be sufficient to induce a similar choice in the rest of the population. As one would reasonably expect, the same result occurs with an increase in the net benefit *c* of using alternative transport modes and/or with a decrease in the negative impact *d* that cars may have on pedestrians, cyclists, bus users and all the other city users that do not take the car.

In the context $b > d \geq 0$, the globally attractive interior stationary state $\bar{x}$ (see case (c) of Proposition 3) is given by $\bar{x} = \sqrt{\frac{a-c}{b-d}}$.

The following proposition illustrates how the attractive interior stationary state $\bar{x}$ and the corresponding value of the average payoff $\bar{\Pi}(\bar{x})$ vary in response to variations in parameter values.

Proposition 6. *The value of* $\bar{x}$ *increases (and, consequently, the number of individuals using cars increases) if the values of the parameters a and d increase or if the values of b and c decrease. Furthermore, in the context b > d > 0, the values of* $\bar{\Pi}(\bar{x})$ *and* $\bar{x}$ *are inversely correlated.*

As the Proposition states, the higher is the net benefit of using the car and/or the negative impact of this choice on alternative transport users, the higher is the incentive to use the car and the number of agents who makes this choice at the equilibrium, but the lower is the correspondent welfare level that agents will enjoy. In other words, if car users have an increasing adverse effect on city users who do not take the car (because of increasing health damages, accidents and difficulty to move across the city with alternative transport systems), then the choice of using the car will obviously spread across the population, but that turns out in the end to be detrimental for everyone (both car users and non-car users). This calls for appropriate transport policies that may "protect" non-car users from the negative impact that they suffer from the rest of the population and may increase, on the contrary, the net benefit of using alternative transport modes.

5. Conclusions

This paper deals with one of most frequently reported problems affecting the life quality and sustainability of modern towns, namely, the extensive and ever increasing use of private cars as the prevailing transport mean. This phenomenon is well-known by long in industrialized countries, where city centers are often congested and highly polluted due to car traffic, but is bound to become extremely relevant also in many developing countries in the future for the large rise in the number of cars' owners that we may expect to occur along with their economic growth in the years to come.

Car owners certainly enjoy higher benefits from the use of their private cars than users of any alternative transport system. Cars, in fact, are undoubtedly more comfortable and potentially faster than most alternative means; what is particularly relevant, they avoid the time spent waiting for public transport at the bus or metro stops and allow their owners to leave and stop whenever they want. On the other hand, cars imply higher costs to their owners in terms of purchase cost, fuel costs, insurance, repairing and maintenance costs, and time spent being "caught" in traffic jams and looking for a parking place. These private costs, together with the collective ones that the car use imposes on the rest of the society (e.g. in terms of environmental and health problems, or productivity loss due to the traffic jam) raise the question of whether and under which conditions the currently widespread choice of using the car can be welfare improving at the individual and collective level.

To examine this issue, we proposed an evolutionary approach that differs from most existing contributions in the present literature on this issue and analyze the possible dynamics that can emerge in a society in which individuals can decide whether to move by car or with alternative transport modes. As shown in the paper, if the relative performance of cars with respect to alternative transport modes increases with the number of car users, then a unique strategy will end up prevailing in the society, so that all agents will choose either to take or not to take the car. If, on the contrary, using the car becomes less and less advantageous as the number of car users increases, then there exists an additional attractive equilibrium beyond the two extreme ones described above, namely a fixed point with mixed strategy in which some agents decide to use the car, while others prefer to use the alternative transport modes[6]. In both cases we show that the no-cars equilibrium can Pareto dominate the other attractive

[6] It must be stressed that the coexistence of alternative transport modes that is observed in reality may also correspond to all the out-of-equilibrium cases that are associated with the transition towards the "pure" equilibria $x=0$ and $x=1$.

equilibria (with all or some car users). In the latter case, moreover, eliminating the negative impacts that car users impose on the rest of the society by introducing, for instance, protected lanes for buses or bicycles, can increase the average welfare level, making all agents equally well-off as in the equilibrium with no cars.

Although the model proposed here is admittedly very simple, in our opinion it can provide an appropriate representation of the dynamics of modal choice[7] and a few basic insights on its policy implications. The present model and its preliminary results can be extended in several directions in the future. In the current analysis, for instance, we considered all the alternative (non-car) transport modes at the aggregate level without distinguishing between them for the sake of simplicity. Each transport mode has instead specific features that should be examined in further details to investigate the possible interactions that may occur between the users of alternative transport modes (e.g. cyclists and bus users). Moreover, it would be interesting to analyze what is the optimal mix among the alternative transport systems given their initial distribution in the society and how policy-makers can achieve this optimal mix through an appropriate intervention on transport fees. We leave these important issues for future research.

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[7] Our dynamic model is not significantly more complex than a static one, while it is able to provide some relevant information, such as the variation of the basins of attraction of the states x=0 e x=1, when they are simultaneously attractive.

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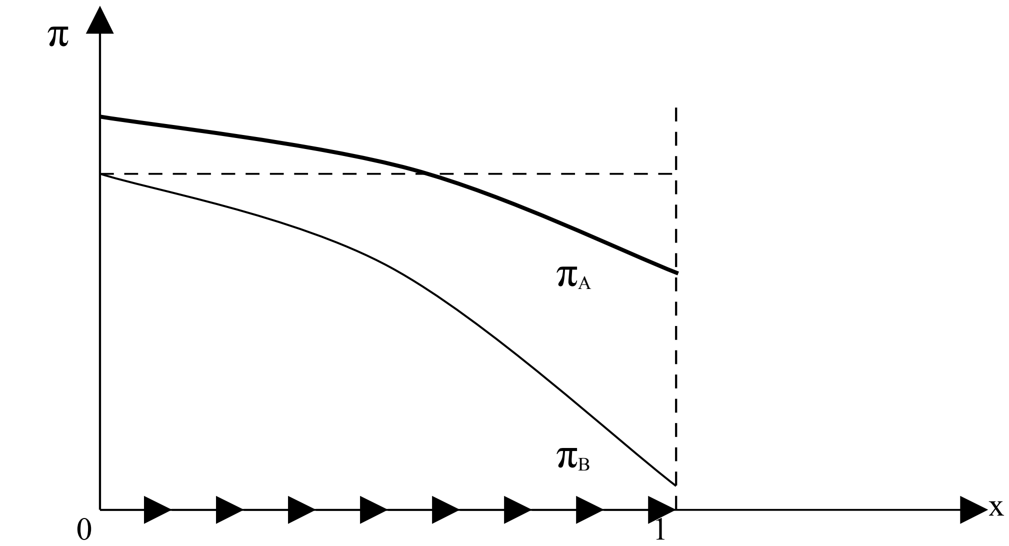

Figure 1: π_B steeper than π_A and always below it (everybody uses the car at the equilibrium)

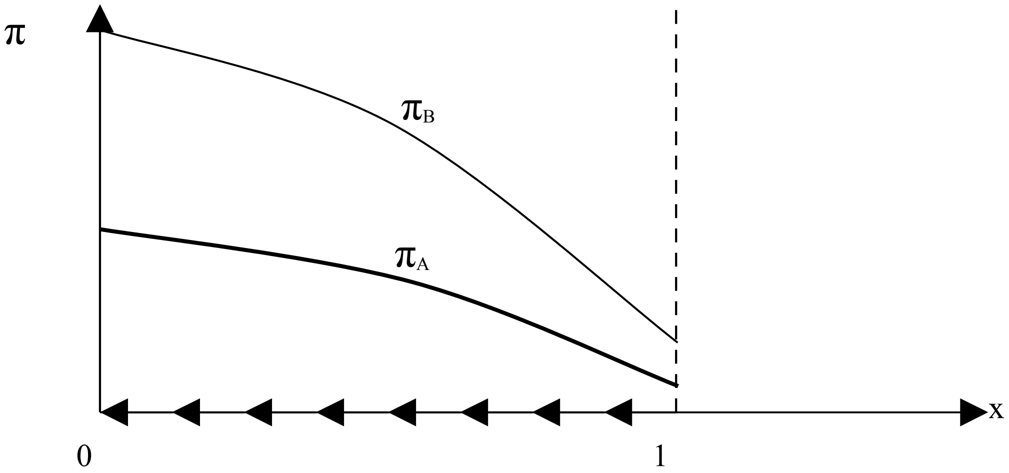

Figure 2: π_B steeper than π_A and always above it (none uses the car at the equilibrium)

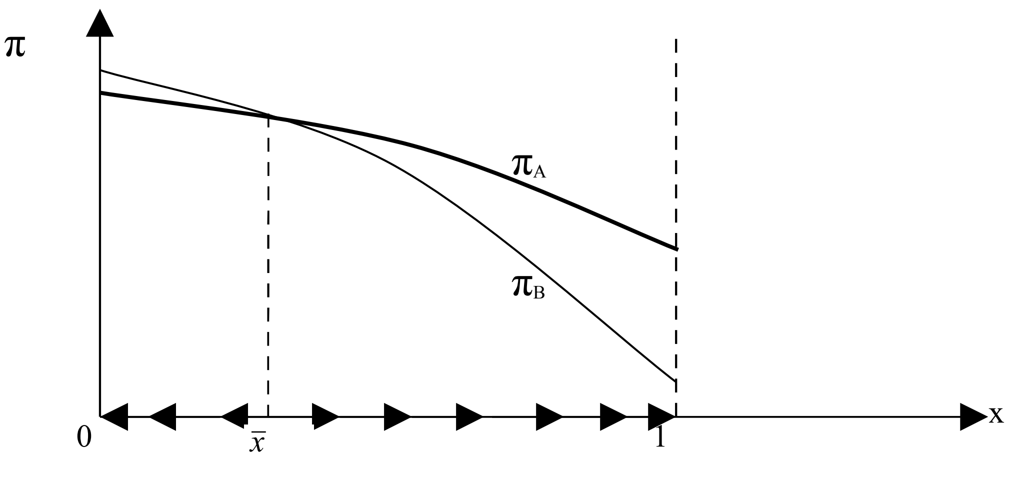

Figure 3: π_B intersects π_A from above: if x is initially above (below) $\bar{x}$, then everybody (none) uses the car.

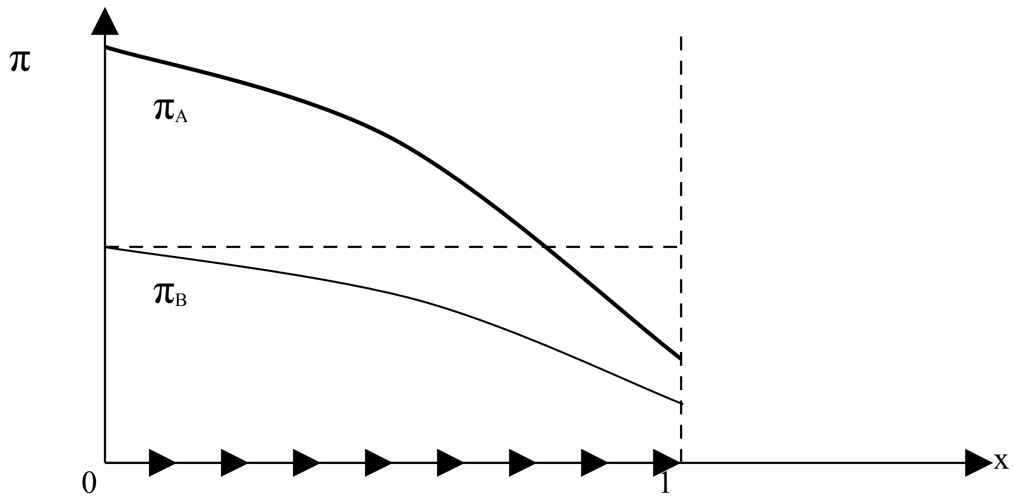

Figure 4: π_A steeper than π_B and always above it (everybody uses the car at the equilibrium)

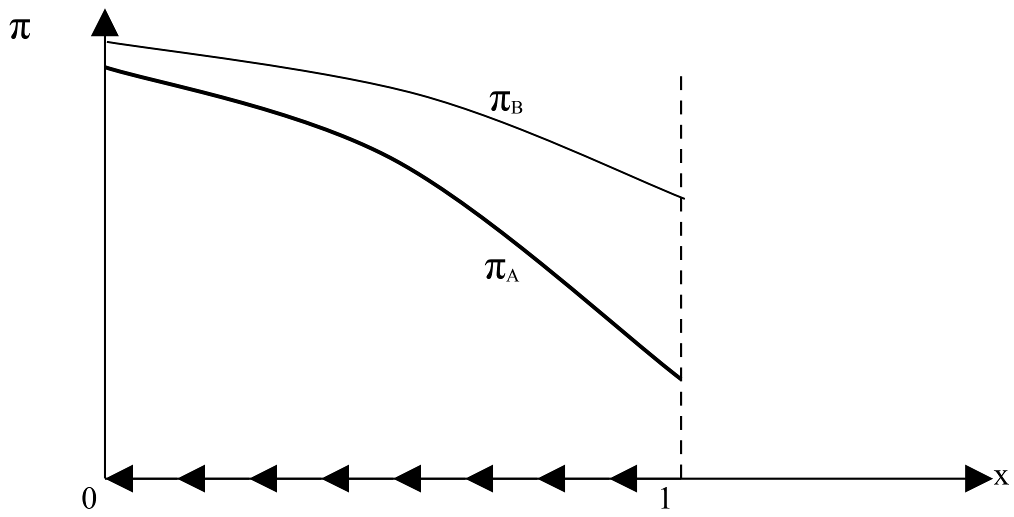

Figure 5: π_A steeper than π_B and always below it (none uses the car at the equilibrium)

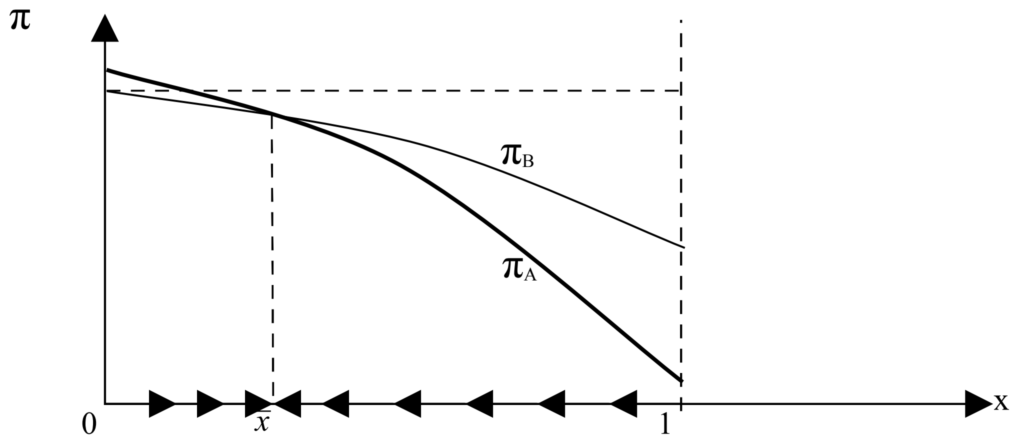

Figure 6: π_A intersects π_B from above: x tends to $\bar{x}$ (stable equilibrium) whatever the initial level of x.