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# Mobility Systems and Economic Growth: a Theoretical Analysis of the Long-Term Effects of Alternative Transportation Policies

Luigi Bonatti, Emanuele Campiglio

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# Mobility Systems and Economic Growth: a Theoretical Analysis of the Long-Term Effects of Alternative Transportation Policies

Luigi Bonatti\*  
Emanuele Campiglio<sup>o</sup>

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## Abstract

We present an example of how public policies affect the evolution of the economy by influencing consumption habits, life styles and work attitudes. In particular, we show that governments can boost long-run growth by moving public investment away from collective transportation systems and towards infrastructures necessary for using private vehicles. Indeed, by augmenting the relative convenience of using private mobility systems, which are those more costly for the households, the government induces them to increase their labor supply so as to afford larger expenditures in transportation. This has long-term welfare implications depending also on the negative externalities associated with transport.

## 1. Introduction

In advanced countries, essential education, health and transportation services are typically made available at relatively cheap prices through subsidized systems that are often directly managed by the government, or alternatively at higher prices through systems to which people can have access by paying a larger fraction of their total cost. As a matter of fact, each country is characterized by its peculiar way to combine these two modalities in providing education, health and transportation services. This paper argues that in general the peculiar mix characterizing a country has effects on its long-run growth and welfare.

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\* University of Trento <luigi.bonatti@unitn.it>

<sup>o</sup> University of Pavia [emanuele.campiglio@eco.unipv.it](mailto:emanuele.campiglio@eco.unipv.it)

In particular, the model presented in this paper intends to offer a simplified treatment of an economy where transportation services are provided by a collective transportation system or by the use of private vehicles on public roads. Individual choices concerning the transportation modes are influenced by government investment in infrastructures that favour mobility systems hinging on private vehicles or that promote the use of collective transportation networks.

The main result of the paper is that—keeping unchanged the fraction of public resources invested in transportation infrastructures—the government can boost long-run growth by investing more in private mobility systems. This is because, by moving public investment away from collective transportation systems and channelling it into the infrastructures that are necessary for the use of private vehicles, the government shifts the households' demand for transportation services in favour of private modalities of transportation, which are those that require relatively more private expenditures. In its turn, this change in the composition of the households' demand for transportation services raises steady-state growth by inducing the households to increase their labor supply so as to afford larger expenditures in transportation. In other words, the composition of public investment matters for long-run growth because, by affecting the relative convenience of different modalities of transportation, it can influence the households' consumption habits, life styles and attitudes regarding market activities. A similar intuition applies to changes in households' preferences: a more intense preference for the use of private modalities of transportation causes the same effects on households behaviour that are induced by an increase in the fraction of public investment devoted to private modalities of transportation.

To the best of our knowledge, there is no other attempt in the literature to model these intuitions.<sup>1</sup> The analytical setup presented here, indeed, offers a formal explanation of why the rapid development of transportation modes based on the mass diffusion of the automobile played a crucial role in driving economic growth in advanced countries. One may observe that the same pattern of development is occurring in developing countries all over the world. It is well known,

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<sup>1</sup> We focus on a channel whereby public investment can affect economic growth that is not explored by the existing literature. As a matter of fact, the latter generally accounts for the impact of public investment on growth by assuming that public capital increases total factor productivity and/or by introducing public capital as an additional input in production functions. For a recent survey of the theoretical and empirical literature on the subject see Romp and de Haan (2007).

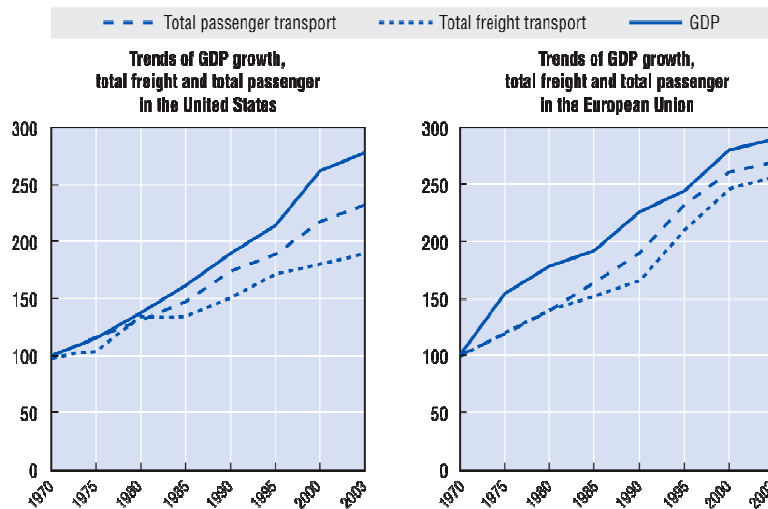
however, that transportation systems can have detrimental side-effects on environmental assets. Therefore, it is not surprising that the long-term welfare effect of a government policy aimed at favouring private modalities of transportation may be negative, in spite of its positive impact on long-run growth. It should be emphasized that this conclusion does not hinge on the fact that a certain quantity of services generated by the private transportation system causes more pollution than the same quantity of services provided by the collective transportation system, but rather on the fact that a policy favouring the use of private vehicles induces the households to spend more and to work more hours, thus stimulating private investment and leading to a more rapid increase in the demand for transportation and in the emission of pollutants.

The paper is organized as follows: section 2 presents the basic model, section 3 discusses some stylized facts, section 4 characterizes the equilibrium trajectory and the balanced growth path of the economy, section 5 treats the long-run welfare implications of the model by introducing negative externalities, and section 6 concludes.

## **2. Some Stylized Facts**

Transport has always been tightly connected to economic growth. Technological innovations in transportation means and infrastructures played a crucial role in the Industrial Revolution and western economic development (Szostak, 1991). Gross domestic product and transport tend to grow together (see figure 1), and there has been a large debate among experts and policy makers on the possibility to “decouple” the two trends (SACTRA, 1999; OECD 2006).

Figure 1 Comparison of trends of GDP and transport growth, 1970-2003 (1970=100)



Source: OECD (2006)

In particular, transport growth has been driven by the expansion of road transport. As is well known, the ascent of automobile as mass means of transportation has immensely increased mobility possibilities in terms of travel distances, flexibility of route, comfort and privacy. Automobile diffusion has triggered a revolution that has gone beyond mobility, drastically modifying social lifestyles, broadening individuals' realization opportunities, stimulating economic growth and consumption. Automobile has also been significant as a productive sector per se: during the last 25 years, the share of U.S. auto industry—which is the first sector in terms of R&D spending—in U.S. GDP floated between 3 and 4% (CAR, 2003). The automotive sector gives employment—if spillovers, downstream and upstream sectors are considered—to around 13 million people, approximately 10% of total U.S. active population. In comparison, the employment contribution of public transport is very limited.<sup>2</sup>

## 2.1 Investment in Transportation Infrastructures and the Structure of the Demand for Transport

A comparison between the experiences of the United States, European Union and Japan gives some support to the hypothesis that government decisions regarding transport infrastructures have relevant effects on the structure of households' demand for transportation

<sup>2</sup> 383.000 people according to APTA [2009].

services. United States, European Union and Japan, indeed, had different policies toward transportation. The U.S. mainly developed its road network, disregarding for long years the expansion and modernization of its rail infrastructures. This was also true for regional and local communities, which typically favoured automobile use rather than collective transportation. In contrast, Japan—although not neglecting the expansion of its road network during the last decades—invested massively in public transportation, building a broad, high-quality rail system. In the years 1992-2003, Japan invested the equivalent of 90 billions euro in its rail infrastructures, while the U.S. invested around 58 billions (OECD, 2007). Considering the size of the territory, Japan invested approximately 242 euro per km<sup>2</sup> in rail infrastructures, while the U.S. only 6 euro.

European countries usually place themselves somewhere in the middle between these two extremes. The long history and compactness of their cities has favoured the development of collective transportation, but road transport is anyway predominant. One can find that in the UE-27 there are 23.2 km of road for each km of rail, while the similar figure for the U.S. is 31.7, thus confirming the greater importance that collective transportation has in Europe. Also Table 1 seems to confirm that with respect the use the automobile Europe is somewhere in between the U.S. and Japan, and that the use of urban collective transportation is more diffuse in Europe than in the U.S.

**Table 1 Passenger transport (billion passenger-km)<sup>3</sup>**

	EU-27	USA	Japan
Passenger car	4,688	7,317	724
Bus+coach	539	275	89
Railway	394	23	396
Tram+metro	85	20	n.a.

Source: European Commission (2009)

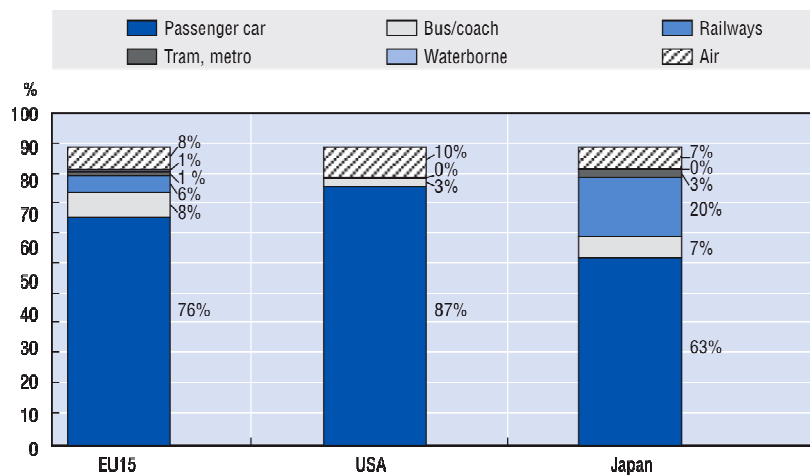
Figure 2 gives further support to the hypothesis of a close relationship between the composition of public investment in transport infrastructures and the relative utilization of each transport mode.<sup>4</sup>

<sup>3</sup> A passenger-kilometer (pkm) is the product between the distance a vehicle travels and the number of vehicle occupants.

<sup>4</sup> Also Newman and Kenworthy (1999) and Kenworthy (2008) provide data on, respectively, 46 and 84 urban areas worldwide, that are consistent with this hypothesis.

American households massively use private vehicles, while in Europe and Japan, where a smaller fraction of public investment in transportation is directed toward the automobile, the use of private vehicle is relatively less diffuse.

Figure 2 Modal split of passenger transport, 2003

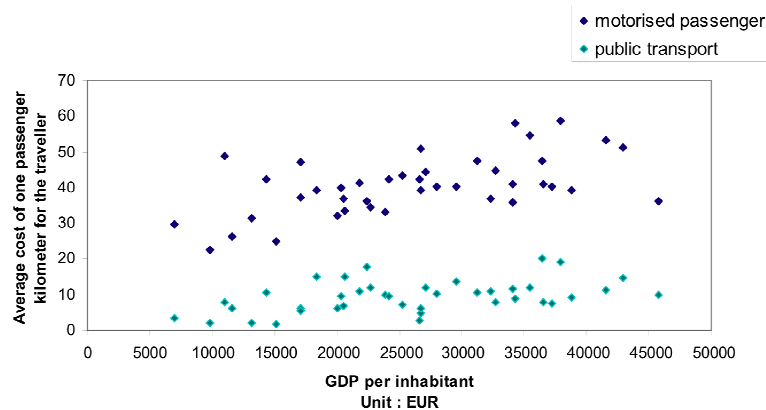


Source: OECD (2006)

## 2.2 Private Transport Modes and Households' Expenditures

The fact that households incur higher costs in the case of private transport systems is common sense: private mobility requires households to purchase a vehicle, to pay maintenance costs, fuel, insurance and vehicle ownership taxes, parking fares and tolls, while to buy a collective transportation service households must only pay a ticket, which typically covers only a fraction of the total cost necessary to produce it. Common sense is also confirmed by the evidence. Figure 3 compares data for 41 European cities concerning the average cost of one passenger-kilometer for users of collective and private motorized transport systems. It can be seen how the average cost of collective transport is systematically lower than the average cost of private transport.

**Figure 3 Average cost of one public transport and private motorised passenger-km for the traveller**



Source: MVV Consulting (2007)

This evidence is consistent with official national statistics. In 2007, EU-27 households spent approximately 950 million euro for transport services (private and collective), which represents the 13.7% of households’ total expenditures for final consumption (1,900 euro per capita) (European Commission, 2008). In the U.S., transport services represents 18% of households’ total expenditures, and 93% of what is spent for transportation by U.S. households is allocated to private transport (BTS, 2009). These values have maintained approximately stable for the last forty years (OECD, 2006). Finally, in 2008, average transport expenditures accounts for only 9.1% of Japanese households’ total expenditures, and 75% of what is spent for transportation by Japanese households is directed toward private transport (Japan Statistical Bureau, 2009).

It should be noticed that these figures shows the existence of a positive correlation—emphasized also by Newman and Kenworthy (1999)—between the relative magnitude of public investment in private transport infrastructures and the share of total expenditures devoted by households to transport services.

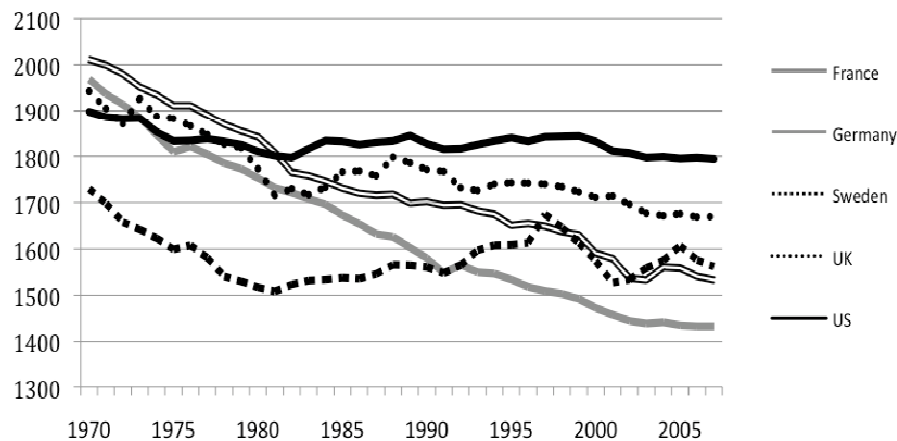
### 2.3 Differences in Working Time

A well-known stylized fact, namely the difference in hours of market labor between the U.S. and Continental Europe, is consistent with our hypothesis that public policies making relatively more convenient for the households to access to costly private transportation services rather than to cheap collective transportation services induce



the households to increase their labor supply so as to afford larger expenditures in services. Figure 4 shows data from OECD (2008), which refer to the evolution of annually worked hours in the U.S. and a representative group of European countries. While the latter all show declining trends, the U.S. hours of market labor has remained roughly stable during the last decades. The topic has recently interested academics, which have offered a variety of different explanations to it, such as the differences in the tax system, unionization and labor market regulations, individual preferences regarding time allocation (Alesina et al., 2006; Blanchard, 2004; Prescott, 2004). Without disregarding the validity of these explanations, we argue that differences in public policies concerning the provision of essential services may have contributed to working time differentials.

Figure 4 Average worked hours per year 1970-2007



Source: OECD (2008)

## 2.4 Transport and Negative Externalities

While improvements in freight transportation have permitted increasingly cheaper, safer and faster movements of goods and materials, progress in passenger mobility has enormously raised individuals' welfare. However, transportation means, and in particular the use of the automobile, generate a variety of negative externalities on environment and relational goods.

First of all, transports are one of the main sources of emissions of greenhouse gases, which are likely to be the primary cause of climate change. In the EU-27, 19.3% of emissions derive from the transport sector, and 71.2% of these emissions are caused by road transportation

(European Commission, 2009).<sup>5</sup> Transportation is also the only productive sector in which emissions, driven by the growth of road transport, have increased in the period 1990-2006 (Eurostat, 2009). If only urban transportation is considered, the picture remains the same. Transport in London, United Kingdom, accounts for 21% of total urban CO<sub>2</sub> emissions, and 49% of these emissions are caused by cars and motorcycles (only 17% by public transport)<sup>6</sup> (Transport for London, 2006). In the city of Milan, Italy, private cars are responsible for 77.4% of total road transport emissions (MVV Consulting, 2007). Besides climate change, whose costs are hardly foreseeable, the main hazards due to pollution reside in health risks and in the worsening of the quality of urban life. According to the European Commission (2007), in the year 2000 the exposure to particulate matter reduced on average statistical life expectancy by nine months in the EU-25.

Another problematic aspect of transportation services is its utilization of resources and energy. In 2004, the share of transport in total energy consumption was 30.7% in the EU-25, and 82.7% of this consumption was due to road transport (only 2.5% to railways) (MVV Consulting, 2007). Newman and Kenworthy (1999) use a set of 46 urban areas worldwide to show that almost everywhere private transportation accounts for more than the 90% of total fuel consumption. Automobiles are also the most inefficient means of transport in terms of energy use. A recent research (CAR, 2003) computed that the U.S. automotive industry alone is consuming 14% of total U.S. steel, 31% of aluminium, 31% of iron, 23% of zinc, 68% of rubber and 23% of glass. The depletion of resources, especially non-renewable ones, is likely to become a major issue in the next decades.

Incidents and related fatalities and injuries must also be included when considering transport negative externalities. In 2007, automobiles caused around 42,500 deaths in EU-27 (equivalent to 86 deaths per million), 41,000 deaths in the U.S. (137 per million), and 5,700 in Japan (45 per million). In the same year, railways fatalities in the EU-27 amounted to 76.

There exists a wide literature focusing on the external costs of transport, which are usually not considered in the official statistics. As a matter of fact, external costs computations are highly dependent on the assumptions made, therefore results from different sources tend to

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<sup>5</sup> Other figures raise the road share to the 93.1% of total transport emissions (Eurostat, 2009).

<sup>6</sup> Other categories considered are road freight (23%) and ground-based aviation (11%).

vary widely. External costs of passenger road transport in the EU-17<sup>7</sup> are estimated by one of the most cited research (INFRAS, 2004) to be approximately 320 million euro per year.<sup>8</sup> External costs of passenger rail transport were computed to be less than 8 million euro.

Not only environmental goods, but also urban social capital and relational goods are likely to be damaged by the diffusion of private transportation. Automobile-dependent cities usually suffer from a degraded urban tissue, with low degrees of public space use and scarce local community interactions (Newman and Kenworthy, 1999). Liveability of neighbourhoods, that can be jeopardized by car congestion, appears to be an essential condition to ensure good quality of life (Leyden, 2003).

### 3. The Basic Model

We consider an economy in discrete time with an infinite time horizon. In this economy there are households, firms and the government. Moreover, we have a single good—which can be interpreted as a composite good and used both for consumption and investment purposes—and two transportation services, one which can be interpreted as the service provided by a collective transportation system and the other which can be interpreted as the service produced by using private cars on public roads. Finally, we assume that agents' expectations are rational, in the sense that they are consistent with the real processes followed by the relevant variables. In this framework, in which there is no source of random disturbances, this implies perfect foresight.

#### 3.1 The Firms

For simplicity and without loss of generality, it is assumed that there is a fixed and large number (normalized to be one) of perfectly competitive firms that are identical and produce the single good  $Y_t$  according to the technology

$$Y_t = A_t K_t^\mu L_t^{1-\mu}, \quad 0 < \mu < 1, \quad (1)$$

where  $A_t$  denotes the state of technology in  $t$ ,  $K_t$  is the stock of capital of the representative firm in  $t$  and  $L_t$  are the units of labor employed in  $t$  by the representative firm. It is assumed that  $A_t$  is a positive function

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<sup>7</sup> EU-15 plus Switzerland and Norway.

<sup>8</sup> External costs include accidents, noise, air pollution, climate change, nature and landscape, life cycle process and urban effects.

of the capital installed by all firms:  $A_t = K_t^{1-\mu}$  (consistently with this formal set-up, one can interpret technological progress as labor augmenting). This assumption combines the idea that learning-by-doing works through each firm's (physical) capital utilization and the idea that knowledge and productivity gains spill over instantly across all firms (see Barro and Sala-i-Martin, 1995). Therefore, in accordance with Frankel (1962), it is supposed that although  $A_t$  is endogenous to the economy, each firm takes it as given, since capital investment on the part of a single firm has only a negligible effect on the aggregate stock of capital.

The net profits (cash flow) of the representative firm in  $t$ ,  $\pi_t$ , are given by

$$\pi = Y_t - W_t L_t - I_t \quad (2)$$

where  $W_t$  and  $I_t$  are, respectively, the wage rate and the investment rate in  $t$ . Note that  $Y_t$  is the numeraire of the system and its price is set to be one.

Each firm's capital stock evolves according to

$$K_{t+1} = I_t + K_t(1-\delta), \quad 0 < \delta < 1, \quad K_0 \text{ given}, \quad (3)$$

where  $\delta$  is a parameter measuring capital depreciation.

The problem of the representative firm amounts to choose  $\{L_t\}_0^\infty$  and  $\{I_t\}_0^\infty$  in order to maximize its discounted sequence of net profits

$$\sum_{t=0}^{\infty} \frac{\pi_t}{\prod_{s=1}^t (1+r_s)} \quad (4)$$

where  $\prod_{s=1}^0 (1+r_s) = 1$ , and  $r_t$  is the market interest rate at time  $t$ .

### 3.2 The Households

For simplicity and without loss of generality, it is assumed that the population is constant and that each household contains one adult, working member of the current generation. Thus, there is a fixed and large number (normalized to be one) of identical adults who take account of the welfare and resources of their actual and prospective descendants. Following Barro and Sala-i-Martin (1995) we model this intergenerational interaction by imagining that the current generation

maximizes utility and incorporates a budget constraint over an infinite future. That is, although individuals have finite lives, we consider immortal extended families (“dynasties”).<sup>9</sup>

The period utility  $u_t$  of the representative household is an increasing function of the consumer good  $C_t$ , transportation services  $T_t$  and  $V_t$ , and leisure  $S_t$ :

$$u_t = \ln(C_t) + \alpha \ln[\xi T_t + (1-\xi)V_t] + \beta \ln(S_t), \alpha > 0, 0 < \xi < 1, \beta > 0. \quad (5)$$

Notice that there are two types of transportation service and that the parameter  $\xi$  captures the households’ subjective preferences regarding the modality whereby to satisfy their demand for transportation services.

Transportation services  $T_t$  and  $V_t$  can be produced according to

$$T_t = K_{T_t}^\gamma X_{T_t}^{1-\gamma}, 0 < \gamma < 1 \quad (6)$$

and

$$V_t = K_{V_t}^\eta X_{V_t}^{1-\eta}, 0 < \eta < \gamma \quad (7)$$

where  $K_{T_t}$  and  $K_{V_t}$  are two specific types of public capital that are available at time  $t$  for producing, respectively,  $T_t$  and  $V_t$ ; while  $X_{T_t}$  and  $X_{V_t}$  are the units of good  $Y_t$  that must be combined at time  $t$  respectively, with  $K_{T_t}$  for obtaining  $T_t$  and with  $K_{V_t}$  for obtaining  $V_t$ . One may think that the government invests in public capital (railways, roads...) by using tax revenues, while the households pay for those intermediate goods that are needed to utilize these capital goods. In other words, households decide how much  $T_t$  and  $V_t$  they want to get by buying the quantities of  $X_{T_t}$  and  $X_{V_t}$  that are necessary—given the existing stocks of  $K_{T_t}$  and  $K_{V_t}$ —for obtaining their desired combination of  $T_t$  and  $V_t$ . Finally, consider that  $T_t$  and  $V_t$  differ because a larger (smaller) fraction of the total value of  $T_t$  ( $V_t$ ) is due to the contribution that the public capital gives to its production: typically,  $T_t$  can be interpreted as the service provided by a collective transportation system (“trains”), while  $V_t$  can be interpreted as the service produced by using private vehicles on public roads (“vehicles”).

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<sup>9</sup> As Barro and Sala-i-Martin (1995, p. 60) point out, “this setting is appropriate if altruistic parents provide transfers to their children, who give in turn to their children, and so on. The immortal family corresponds to finite-lived individuals who are connected via a pattern of operative intergenerational transfers that are based on altruism”.

The period budget constraint of the representative household is given by

$$C_t + X_{Vt} + X_{Tt} + B_{t+1} \leq \pi_t + L_t W_t + (1+r_t)B_t - \tau_t, \quad B_0 \text{ given}, \quad (8)$$

where  $B_t$  is a (one-period maturity) bond issued by the government at time  $t$ , and  $\tau_t$  are the net transfers (“taxes”) from the representative household to the government in  $t$ . Notice that taxation is not distortionary and that households are the firms’ owners, thus receiving  $\pi_t$  in each  $t$  as dividend payments.

Furthermore, the representative household faces a time constraint:

$$L_t + S_t \leq H, \quad (9)$$

where  $H$  is the household’s total time endowment.

The problem of the representative household amounts to choose  $\{L_t\}_0^\infty$ ,  $\{C_t\}_0^\infty$ ,  $\{X_{Vt}\}_0^\infty$ ,  $\{X_{Tt}\}_0^\infty$  and  $\{B_{t+1}\}_0^\infty$  in order to maximize its discounted sequence of period utilities

$$\sum_{t=0}^{\infty} \theta^t u_t, \quad 0 < \theta < 1 \quad (10)$$

where  $\theta$  is a time-preference parameter.

### 3.3 The Government

The government decides what fraction  $g$  of  $Y_t$  to invest in any period in public capital:

$$I_{Vt} + I_{Tt} = gY_t, \quad 0 < g < 1. \quad (11)$$

Moreover, the government decides what fraction  $\phi$  ( $1-\phi$ ) of total public investment to devote to the accumulation of  $K_{Vt}$  ( $K_{Tt}$ ):

$$I_{Vt} = \phi g Y_t, \quad 0 < \phi < 1, \quad (12)$$

$$I_{Tt} = (1-\phi)g Y_t. \quad (13)$$

The two types of public capital evolve according to

$$K_{Vt+1} = I_{Vt} + (1-\delta)K_{Vt}, \quad K_{V0} \text{ given}, \quad (14)$$

$$K_{Tt+1} = I_{Tt} + (1-\delta)K_{Tt}, \quad K_{T0} \text{ given.}^{10} \quad (15)$$

The government’s budget constraint is

$$(1+r_t)B_t + I_{Vt} + I_{Tt} \leq \tau_t + B_{t+1}. \quad (16)$$

The government must also satisfy a no-Ponzi intertemporal constraint.<sup>11</sup>

<sup>10</sup> For simplicity we are assuming that all types of capital depreciates at the same rate  $\delta$ .

### 3.4 Markets Equilibrium

Labor market equilibrium requires that in each t

$$L_t^s = L_t^d, \quad (17)$$

where the superscript “s” (“d”) denotes the quantity supplied (demanded) of that variable.

Equilibrium in the market for good  $Y_t$  requires that in each t

$$Y_t = C_t + X_{Vt} + X_{Tt} + I_t + I_{Vt} + I_{Tt}. \quad (18)$$

Equilibrium in the bond market requires that in each t

$$B_t^s = B_t^d. \quad (19)$$

## 4. Equilibrium Dynamics and Balanced Growth Path

Using the market equilibrium conditions and solving the agents' optimization problems (see the Appendix), we obtain the system of difference equations in  $Q_t \equiv \frac{K_t}{K_{Tt}}$ ,  $M_t \equiv \frac{X_{Vt}}{K_{Vt}}$  and  $Z_t \equiv \frac{X_{Vt}}{K_{Tt}}$  governing the equilibrium path of the economy (see the Appendix for the derivation):

$$\Psi(Q_{t+1}, Q_t, M_t, Z_t) = (1-g)Q_t L_t^{1-\mu} - \left[ \frac{\xi(1-\gamma)M_t^\eta}{(1-\xi)(1-\eta)} \right]^{\frac{1}{\gamma}} \frac{[1+\alpha(1-\gamma)]}{\alpha(1-\gamma)} - \frac{[1+\alpha(1-\eta)]Z_t}{\alpha(1-\eta)} - Q_{t+1}(1+\rho_t) + (1-\delta)Q_t = 0, \quad (20)$$

$$\Phi(M_{t+1}, Z_{t+1}, Q_t, M_t, Z_t) = (1+\rho_t) \frac{Z_{t+1}}{M_{t+1}} - \phi g L_t^{1-\mu} Q_t - (1-\delta) \frac{Z_t}{M_t} = 0 \quad (21)$$

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<sup>11</sup> Since in this framework the Ricardian equivalence holds, it is immaterial to determine the time profile of  $T_t$  and  $B_{t+1}$ .

$$\Lambda(Q_{t+1}, M_{t+1}, Z_{t+1}, Q_t, M_t, Z_t) = \theta[\mu L_{t+1}^{1-\mu} + 1 - \delta] - (1 + \rho_t) \left\{ \frac{\left[ \frac{\xi(1-\gamma)M_{t+1}^\eta}{(1-\xi)(1-\eta)} \right]^{\frac{1}{\gamma}} + \frac{(1-\gamma)Z_{t+1}}{(1-\eta)}}{\left[ \frac{\xi(1-\gamma)M_t^\eta}{(1-\xi)(1-\eta)} \right]^{\frac{1}{\gamma}} + \frac{(1-\gamma)Z_t}{(1-\eta)}} \right\} = 0, \quad (22)$$

where

$$\rho_t \equiv \frac{K_{Tt+1} - K_{Tt}}{K_{Tt}} = (1 - \varphi)gL_t^{1-\mu}Q_t - \delta \quad (23)$$

and  $L_t = f(Q_t, M_t, Z_t)$  is implicitly defined as a function of  $Q_t$ ,  $M_t$  and  $Z_t$  by

$$L_t^\mu \left\{ \left[ \frac{\xi(1-\gamma)M_t^\eta}{(1-\xi)(1-\eta)} \right]^{\frac{1}{\gamma}} + \frac{(1-\gamma)Z_t}{(1-\eta)} \right\} = \frac{(H - L_t)(1-\mu)\alpha(1-\gamma)Q_t}{\beta}. \quad (24)$$

A balanced growth path (BGP) can be characterized by setting  $Q_{t+1} = Q_t = Q$ ,  $M_{t+1} = M_t = M$  and  $Z_{t+1} = Z_t = Z$  in (20)-(24). Hence, a BGP is a triple of values of  $Q$ ,  $M$  and  $Z$ , say  $(Q^0 > 0, M^0 > 0, Z^0 > 0)$ , that satisfies (see the Appendix)

$$Q = \frac{\theta\mu L^{1-\mu} - (1-\delta)(1-\theta)}{g(1-\varphi)L^{1-\mu}}, \quad (25)$$

$$Z = \frac{\varphi M}{(1-\varphi)} \quad (26)$$

and

$$M = \frac{m(L)}{\varphi}, \quad (27)$$

where

$$m(L) = \frac{(1-\eta)[\theta\mu L^{1-\mu} - (1-\delta)(1-\theta)]}{(\gamma-\eta)g} \left\{ 1 - g - \frac{[\theta\mu L^{1-\mu} - (1-\delta)(1-\theta)]}{L^{1-\mu}} - \frac{(H-L)(1-\mu)[1 + \alpha(1-\gamma)]}{\beta L} \right\} \quad (28)$$

and  $L$  is defined implicitly—as a function of the parameters—by



$$l(L, \varphi, \xi) = \left[ \frac{\xi(1-\gamma)}{(1-\xi)(1-\eta)} \right]^{\frac{1}{\gamma}} \left[ \frac{m(L)}{\varphi} \right]^{\frac{\eta}{\gamma}} \frac{[1+\alpha(1-\gamma)](1-\varphi)}{\alpha(1-\gamma)} + \frac{[1+\alpha(1-\eta)]m(L)}{\alpha(1-\eta)} - \frac{[\theta\mu L^{1-\mu} - (1-\delta)(1-\theta)]}{g} \left\{ 1-g - \frac{[\theta\mu L^{1-\mu} - (1-\delta)(1-\theta)]}{L^{1-\mu}} \right\} = 0. \quad (29)$$

One can show for reasonable parameter values that there exists a unique  $L > 0$ , say  $L^\circ$ , which satisfies (29) and is consistent with both  $Q > 0$  and  $M > 0$  (see the Appendix). Hence,  $(Q^\circ > 0, M^\circ > 0, Z^\circ > 0)$  can exist and be unique. Moreover, by linearizing (20)-(22) around this unique BGP, one can exhibit numerical examples showing that  $(Q^\circ > 0, M^\circ > 0, Z^\circ > 0)$  is saddle-path stable: in these examples, there exists a unique equilibrium trajectory in a neighborhood of  $(Q^\circ > 0, M^\circ > 0, Z^\circ > 0)$  that converges to it (see the Appendix). Finally, the following proposition can be demonstrated regarding this BGP:

**Proposition 1.** An increase (a decrease) in  $\varphi$ , i.e., in the fraction of total government investment devoted to the accumulation of the public capital utilized for private transportation (“roads”), has a positive (negative) effect on the steady-state rate of economic growth, even if the government keeps constant the fraction  $g$  of good  $Y_t$  that in each period it wants to invest in public capital. Similarly, a decrease (an increase) in  $\xi$ , i.e., in the households’ preference for using collective transportation rather than private transportation has positive (negative) effect on the steady-state rate of economic growth.

**Proof:** By considering (23) and (25), one can easily check that along a BGP the economy grows at rate  $\rho^\circ = \theta[\mu(L^\circ)^{1-\mu} + 1 - \delta] - 1$ , which is monotonically increasing in  $L^\circ$ . Moreover, one can prove that  $L^\circ$  is monotonically increasing in  $\varphi$  and monotonically decreasing in  $\xi$  (see the Appendix).

The intuition underlying Proposition 1 is that by moving public investment away from collective transportation systems and channelling it into the infrastructures that are necessary for the use of private vehicles, the government shifts the households’ demand for transportation services in favour of private modalities of transportation, which are those that require relatively more private expenditures. In its turn, this change in the composition of the households’ demand for transportation services boosts long-run growth by inducing the households to increase their labor supply so as to afford the larger expenditures in transportation. In other words, the composition of public investment matters for long-run growth because, by affecting the relative convenience of different modalities of transportation, it can influence the households’ consumption habits, life styles and attitudes

regarding market activities. A similar intuition applies to changes in households' preferences: a more intense preference for the use of private modalities of transportation shifts households' demand towards more costly transportation services, thus increasing their labor supply and boosting economic growth.

## 5. Negative Externalities and Long-Run Welfare

We extend the model by assuming that the representative household gets some utility from an environmental asset ("air"). Hence, we rewrite the period utility function of the representative household as

$$u_t = \ln(C_t) + \alpha \ln[\xi T_t + (1 - \xi)V_t] + \beta \ln(S_t) + \kappa \ln(R_t), \kappa > 0, \quad (30)$$

where  $R_t$  is a common property resource whose quality tends typically to improve or to deteriorate. Thus, it makes sense to treat  $R_t$  as a renewable resource. Moreover, we assume that the ability of  $R_t$  to regenerate declines with the amount of pollution created by transportation services:

$$R_{t+1} - R_t = z(R_t, T_t, V_t), \quad z_T < 0, \quad z_V < 0, \quad R_0 \text{ given.} \quad (31)$$

In particular, we specify a functional form for  $z(\cdot)$  by modifying the logistic model, which is one of the simplest and best known functional specifications for the law of motion of a renewable resource (see Conrad, 1987):

$$z(R_t, T_t, V_t) = \chi R_t \left\{ 1 - \frac{R_t [\zeta T_t + (1 - \zeta)V_t]}{\nu} \right\}, \quad \chi > 0, \nu > 0, 0 < \zeta < 1 \quad (32)$$

where the parameter  $\chi$  can be interpreted as the intrinsic growth rate of  $R_t$ ,  $\nu$  is a parameter on which depends the impact of the households' activities on the future level of the common property resource and  $\zeta$  measures the relative contribution of the two types of transportation service to the creation of pollution. Note that each single household can ignore the negative effect of its own activity on the future level of  $R_t$ , since its impact on the evolution of  $R_t$  is negligible. However, the aggregate impact of the households' activities on the future quality of the renewable resource is significant because of the large number of households populating the economy.

Given (31)-(32), the equilibrium path of the economy is governed by the system (20)-(24) and by (see the Appendix)

$$\frac{N_{t+1}}{(1 + \rho_t)} - N_t = \chi N_t \left\{ 1 - \frac{N_t}{\nu M_t^\eta} \left[ \zeta \left[ \frac{\xi(1 - \gamma)}{(1 - \xi)(1 - \eta)} \right]^{\frac{1-\gamma}{\gamma}} M_t^{\frac{\eta}{\gamma}} + (1 - \zeta)Z_t \right] \right\} \quad (33)$$

Where  $N_t \equiv R_t K_{Tt}$ .

Hence, a BGP, say  $(Q^\circ > 0, M^\circ > 0, Z^\circ > 0, N^\circ > 0)$ , is a quadruple of values of  $Q$ ,  $M$ ,  $Z$  and  $N$  that satisfies (25)-(29) and

$$N = \left[ \frac{\rho}{(1+\rho)\chi} + 1 \right] \nu M^\eta \left\{ \zeta \left[ \frac{\xi(1-\gamma)}{(1-\xi)(1-\eta)} \right]^{\frac{1-\gamma}{\gamma}} M^{\frac{\eta}{\gamma}} + (1-\zeta)Z \right\}^{-1}. \quad (34)$$

One can easily verify that along a BGP characterized by  $(Q^\circ > 0, M^\circ > 0, Z^\circ > 0, N^\circ > 0)$ , perpetual growth ( $\rho^\circ > 0$ ) implies that environmental quality tends to deteriorate forever. This captures the fact that in this framework perpetual growth entails unbounded increase in the emissions damaging the environment, since there is no technological progress limiting the amount of pollution generated by a given quantity of transportation services.

Suppose that the economy is moving along its BGP. In this case, the representative household's discounted sequence of utilities at time  $t$  is (see the Appendix for the derivation)

$$\begin{aligned} \sum_{i=0}^{\infty} \theta^i u_{t+i}^\circ &= \left\{ (1 + \alpha - \kappa) \ln(K_{Tt}) + \ln \left[ \left[ \frac{\xi(1-\gamma)}{(1-\xi)(1-\eta)} \right]^{\frac{1}{\gamma}} (M^\circ)^{\frac{\eta}{\gamma}} + \frac{(1-\gamma)}{(1-\eta)} Z^\circ \right] \right\} - \\ &- \ln[\alpha(1-\gamma)] + \beta \ln(H - L^\circ) - \\ &- \alpha \eta \ln(M^\circ) + \frac{\alpha}{(1-\theta)} \ln \left\{ \zeta \left[ \frac{\xi(1-\gamma)}{(1-\xi)(1-\eta)} \right]^{\frac{1-\gamma}{\gamma}} (M^\circ)^{\frac{\eta}{\gamma}} + (1-\zeta)Z^\circ \right\} + \kappa \ln(N^\circ) \left. \right\} + \\ &+ \frac{\theta(1 + \alpha - \kappa) \ln(1 + \rho^\circ)}{(1-\theta)^2}, \end{aligned} \quad (35)$$

where  $K_{Tt}$  is given at time  $t$ .

Equation (35) allows us to compare the welfare of the representative households located in two economies that are moving along their respective BGP and that differ only because their authorities are devoting different fractions of total public investment to the two modalities of transportation. In this case, indeed, one can prove for reasonable parameter values that the following proposition holds:

**Proposition 2.** Consider two economies that at time  $t$  are moving along their respective balanced growth path and that have the same  $K_{Tt}$

and parameters values, except for  $\varphi$ , namely for the fraction of total public investment devoted to the private transportation system. If the households are particularly sensitive to pollution, i.e., if  $\kappa$  is relatively large, the economy whose  $\varphi$  is larger has the lower level of welfare, i.e., its households have a smaller discounted sequence of utilities along the balanced growth path.

**Proof:** See the Appendix.

It is worth to recall that the economy which is allocating relatively more resources to investment in the private transportation system has also the lower fraction of households' time devoted to leisure and the higher steady-state rate of growth. Hence, a possible trade-off between long-run growth and welfare emerges. Furthermore, one should emphasize that Proposition 2 does not hinge on the fact that a certain quantity of services generated by the private transportation system causes more pollution than the same quantity of services provided by the collective transportation system (it holds for any value of  $\zeta$ ), but rather on the fact that a larger  $\varphi$  induces the households to spend more and to work more hours, thus stimulating private investment and leading to a more rapid increase in the demand for transportation and in the emission of pollutants.

## 6. Conclusions

We have presented an example of how public policies can affect the evolution of the economy by influencing consumption habits, life styles and work attitudes. In particular, we have shown that governments can boost long-run growth by moving public investment away from collective transportation systems and towards infrastructures necessary for using private vehicles. Indeed, by augmenting the relative convenience of using private mobility systems, the government shifts the households' demand for transportation services in favour of private modalities of transportation, which are those more costly for the households. In this way, the government induces them to increase their labor supply so as to afford larger expenditures in transportation. A similar intuition applies to changes in households' preferences: a more intense preference for the use of private modalities of transportation shifts households' demand towards more costly transportation services, thus increasing their labor supply and boosting economic growth.

We have also introduced the negative externalities associated with transportation and analyzed the welfare implications of public policies

regarding transportation systems, showing that a trade-off between long-run growth and welfare may emerge.

One should notice that we have studied the effects of government's investment policies on long-run growth and welfare by assuming that taxation is not distortionary and by keeping unchanged the fraction of the single composite good produced in the economy that is invested by the government. Indeed, we intended to focus on the effects that the composition of public expenditures can have on the evolution of the economy because of its impact on the households' optimal trade-off between income and leisure. These effects can be relevant also with respect to public policies regarding education and health. For instance, it is likely that changes in the fraction of public resources devoted to subsidize the households' access to relatively costly private schools (or hospitals) rather than to relatively cheap public schools (or hospitals) have not only a redistributive impact but also effects on labor supply. Given their important implications for long-run growth and welfare, these effects of public policies deserve further theoretical and empirical analysis.

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## 7 Appendix

### 7.1 Derivation of the System (20)-(24)

From firms' first-order condition with respect to labor, we get:

$$L_t = \left[ \frac{(1-\mu)A_t K_t^\mu}{W_t} \right]^{\frac{1}{\mu}}, \quad (\text{A1})$$

By using (A1) to obtain the labor demanded by each firm producing  $Y_t$ , the intertemporal problem of the representative firm can be solved by maximizing

$$\sum_{v=0}^{\infty} \left\{ \frac{\mu \left( \frac{(1-\mu)^{1-\mu} A_{t+v} K_{t+v}^\mu}{W_{t+v}^{1-\mu}} \right)^{\frac{1}{\mu}} - I_{t+v} - \sigma_{t+v} [K_{t+v+1} - I_{t+v} - (1-\delta)K_{t+v}]}{\prod_{s=1}^v (1+r_{t+s})} \right\}$$

with respect to  $I_t$ ,  $K_{t+1}$  and the Lagrange multiplier  $\sigma_t$ , and then by eliminating  $\sigma_t$ , thus obtaining:

$$\mu L_{t+1}^{1-\mu} + 1 - \delta = 1 + r_{t+1}, \quad (\text{A2})$$

$$K_{t+1} = I_t + (1-\delta)K_t. \quad (\text{A3})$$

An optimal path must also satisfy the transversality condition

$$\lim_{v \rightarrow \infty} \frac{K_{t+v}}{\prod_{s=1}^v (1+r_{t+s})} = 0. \quad (\text{A4})$$

Moreover, one can solve the households' problem by maximizing

$$\sum_{v=0}^{\infty} \theta^v \left\{ \ln(C_{t+v}) + \alpha \ln[\xi K_{Tt+v}^{\gamma} X_{Tt+v}^{1-\gamma} + (1-\xi) K_{Vt+v}^{\eta} X_{Vt+v}^{1-\eta}] + \right. \\ \left. + \beta \ln(H - L_{t+v}) + \lambda_{t+v} [B_{t+v}(1+r_{t+v}) + \pi_{t+v} + W_{t+v} L_{t+v} - \right. \\ \left. - \tau_{t+v} - C_{t+v} - X_{Tt+v} - X_{Vt+v} - B_{t+v+1}] \right\}$$

with respect to  $C_t, X_{Tt}, X_{Vt}, L_t, B_{t+1}$  and the Lagrangean multiplier  $\lambda_t$ , and then by eliminating  $\lambda_t$ , thus obtaining:

$$\frac{W_t}{C_t} = \frac{\beta}{(H - L_t)}, \quad (A5)$$

$$\alpha(1-\gamma)C_t = \frac{\xi K_{Tt}^{\gamma} X_{Tt}^{1-\gamma} + (1-\xi) K_{Vt}^{\eta} X_{Vt}^{1-\eta}}{\xi K_{Tt}^{\gamma} X_{Tt}^{-\gamma}}, \quad (A6)$$

$$X_{Tt} = K_{Tt} \left[ \frac{\xi(1-\gamma)}{(1-\xi)(1-\eta)} \left( \frac{X_{Vt}}{K_{Vt}} \right)^{\eta} \right]^{\frac{1}{\gamma}}, \quad (A7)$$

$$\frac{C_{t+1}}{C_t} = \theta(1+r_{t+1}), \quad (A8)$$

$$C_t + X_{Vt} + X_{Tt} + B_{t+1} = \pi_t + L_t W_t + (1+r_t) B_t - \tau_t. \quad (A9)$$

The households' optimal path must satisfy the transversality condition

$$\lim_{v \rightarrow \infty} \frac{\theta^v B_{t+1+v}}{C_{t+v}} = 0. \quad (A10)$$

By using (A6) and (A7), one can obtain

$$C_t = \frac{K_{Tt} \left[ \frac{\xi(1-\gamma)}{(1-\xi)(1-\eta)} \left( \frac{X_{Vt}}{K_{Vt}} \right)^{\eta} \right]^{\frac{1}{\gamma}} + \frac{(1-\gamma)X_{Vt}}{(1-\eta)}}{\alpha(1-\gamma)}. \quad (A11)$$

By using (1), (3), (12)-13), (A7) and (A11), one can rewrite (18) as (20).



By using (12) to substitute for  $I_{V_t}$  in (14), one obtains  $K_{V_{t+1}} = \phi g Y_t + (1 - \delta) K_{V_t}$ , which—divided by  $K_{T_t}$ —gives (21).

By using (A2) and (A11), one can rewrite (A8) as (22).

By using (13) to substitute for  $I_{T_t}$  in (15), one obtains  $K_{T_{t+1}} = (1 - \phi) g Y_t + (1 - \delta) K_{T_t}$ , which—divided by  $K_{T_t}$ —gives (23).

Finally, by using (A1) and (A11), one can rewrite (A5) as (24).

## 7.2 Derivation of the System (25)-(29)

By setting  $Q_{t+1} = Q_t = Q$ ,  $M_{t+1} = M_t = M$  and  $Z_{t+1} = Z_t = Z$  in (20)-(24), equation (21) becomes

$$(1 + \rho) \frac{Z}{M} = \phi g L^{1-\mu} Q + (1 - \delta) \frac{Z}{M}, \quad (\text{A12})$$

equation (22) becomes

$$\theta [\mu L^{1-\mu} + 1 - \delta] = 1 + \rho \quad (\text{A13})$$

and equation (23) becomes

$$\rho = (1 - \phi) g L^{1-\mu} Q - \delta. \quad (\text{A14})$$

Equations (A13) and (A14) allow us to obtain (25). Equations (A12) and (A13)—together with (25)—allow us to obtain (26).

By setting  $Q_{t+1} = Q_t = Q$ ,  $M_{t+1} = M_t = M$  and  $Z_{t+1} = Z_t = Z$  and by using (25) and (26), equations (20) and (24) can be written, respectively, as

$$\begin{aligned} & \left[ \frac{\xi(1-\gamma)M^\eta}{(1-\xi)(1-\eta)} \right]^\frac{1}{\gamma} = \\ & \frac{\left\{ \frac{(1-g)[\theta\mu L^{1-\mu} - (1-\theta)(1-\delta)]}{g} - \frac{[\theta\mu L^{1-\mu} - (1-\theta)(1-\delta)]^2}{gL^{1-\mu}} - \frac{\phi M[1 + \alpha(1-\eta)]}{(1-\eta)\alpha} \right\}}{(1-\phi)[1 + \alpha(1-\gamma)]} \end{aligned} \quad (\text{A15})$$

and as

$$\left[ \frac{\xi(1-\gamma)M^\eta}{(1-\xi)(1-\eta)} \right]^\frac{1}{\gamma} = \frac{\left\{ \frac{(H-L)(1-\mu)[\theta\mu L^{1-\mu} - (1-\theta)(1-\delta)]}{\beta g L} - \frac{\phi M}{(1-\eta)\alpha} \right\}}{(1-\phi)} \quad (\text{A16})$$

Equations (A15) and (A16) allow us to obtain (27) and (28).

Finally, by using (27) to substitute for  $M$  in (A15), one can obtain (29).

### 7.3 Existence and Uniqueness of the Balanced Growth Path characterized by $(Q^\circ > 0, M^\circ > 0, Z^\circ > 0)$

We know that  $L^\circ$  must be a value of  $L > 0$  which satisfies  $l(L, \varphi, \xi) = 0$  and is consistent with both  $Q > 0$  and  $M = \frac{m(L)}{\varphi} > 0$ . Let us consider reasonable parameter values such that:

$$H^{1-\mu} \theta \mu > (1-\theta)(1-\delta), \quad (\text{A17})$$

$$1-g-\theta\mu \geq 0, \quad (\text{A18})$$

$$\frac{(H-\bar{L})(1-\mu)[1+\alpha(1-\gamma)]}{\beta\bar{L}} > 1-g, \quad \bar{L} \equiv \left[ \frac{(1-\theta)(1-\delta)}{\theta\mu} \right]^{\frac{1}{1-\mu}}, \quad (\text{A19})$$

$$\theta\mu\tilde{L}^{1-\mu} [H\mu + (1-\mu)\tilde{L}] > H(1-\theta)(1-\delta), \quad (\text{A20})$$

where  $\tilde{L} > \bar{L}$  is the value of  $L > 0$

satisfying  $\frac{(H-L)(1-\mu)[1+\alpha(1-\gamma)]}{\beta L} = 1-g-\theta\mu + \frac{(1-\theta)(1-\delta)}{L^{1-\mu}}$  (given

(A17), one can check that  $\tilde{L}$  is unique).

Given (A17)-(A20), one can also check that  $m(L) \leq 0$  for  $L$  such that  $\bar{L} \leq L \leq \tilde{L}$ , and that  $m(L) > 0$  both for  $0 \leq L < \bar{L}$  and for  $\tilde{L} < L \leq H$ . Thus, one can rule out the possibility that  $\bar{L} \leq L^\circ \leq \tilde{L}$ , since this would be inconsistent with  $M^\circ > 0$ . Furthermore, one can rule out the possibility that  $0 < L^\circ < \bar{L}$  by verifying that  $0 < L < \bar{L}$  implies both  $Q < 0$  and  $l(L, \varphi, \xi) > 0$ . One can also check that both the function  $m(L)$  and the function  $l(L, \varphi, \xi)$  are continuous and monotonically increasing in  $L$  for  $\tilde{L} \leq L \leq H$ :

$$\frac{\partial m(L)}{\partial L} > 0, \quad \tilde{L} \leq L \leq H, \quad (\text{A21})$$

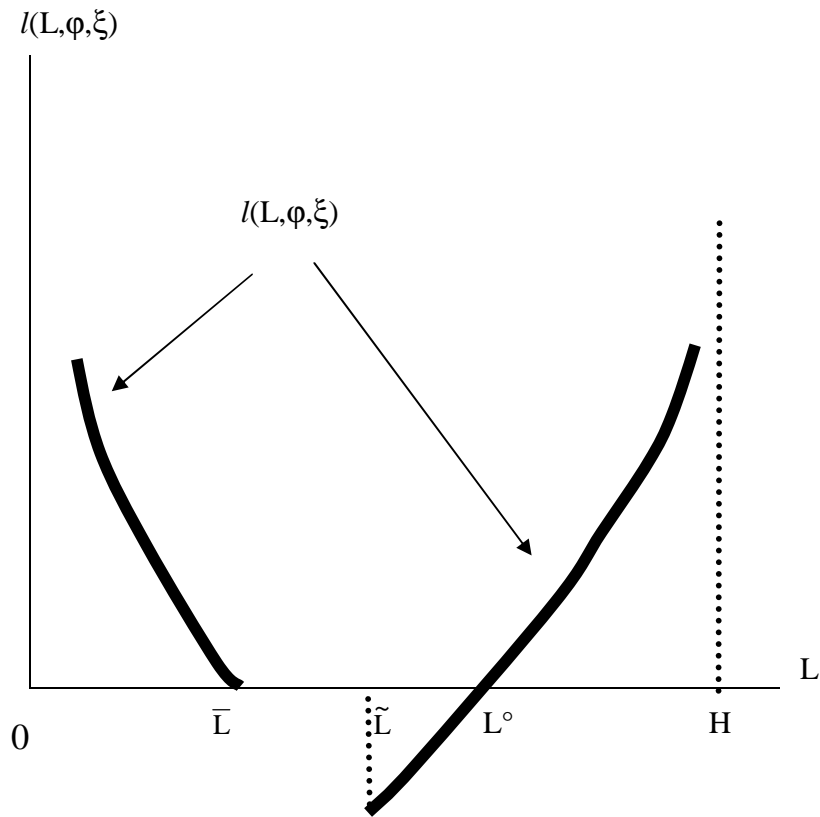
$$\frac{\partial l(L, \varphi, \xi)}{\partial L} > 0, \quad \tilde{L} \leq L \leq H. \quad (\text{A22})$$

Finally, one can verify that  $l(L, \varphi, \xi)$  is such that  $l(L, \varphi, \xi) \Big|_{L=\tilde{L}} < 0$

and  $l(L, \varphi, \xi) \Big|_{L=H} > 0$ . Hence, there exists a unique value of  $L$ , say  $L^\circ$ ,

which satisfies  $l(L, \varphi, \xi) = 0$  and is consistent with both  $Q > 0$  and  $m(L) > 0$ . Notice that  $L^\circ$  is such that  $\tilde{L} < L^\circ < H$  (see figure A.1).

Figure A.1 Existence of a unique balanced growth path characterized by  $(Q^>0, M^>0, Z^>0)$



#### 7.4 Local Stability Analysis of $(Q^>0, M^>0, Z^>0)$

By linearizing (20)-(22) around  $(Q^>0, M^>0, Z^>0)$ , one can find the characteristic equation of the system thus obtained. This characteristic equation is the following:

$$\begin{aligned} &\omega^3 - (a_{11} + a_{22} + a_{33})\omega^2 + (a_{11}a_{22} + a_{11}a_{22} + a_{22}a_{33} - a_{23}a_{32} - a_{12}a_{21} - \\ &- a_{13}a_{31})\omega - a_{11}a_{22}a_{33} - a_{12}a_{23}a_{31} + a_{11}a_{23}a_{32} + a_{12}a_{21}a_{33} - \\ &- a_{13}a_{21}a_{32} + a_{13}a_{22}a_{31} = 0, \end{aligned} \quad (A23)$$

where  $\omega_1$ ,  $\omega_2$  and  $\omega_3$  are the eigenvalues of the system,

$$\begin{aligned}
a_{11} &= \frac{-\Psi_{Q_t}}{\Psi_{Q_{t+1}}}, \quad a_{12} = \frac{-\Psi_{M_t}}{\Psi_{Q_{t+1}}}, \quad a_{13} = \frac{-\Psi_{Z_t}}{\Psi_{Q_{t+1}}}, \\
a_{21} &= \frac{-\Phi_{Z_{t+1}} \left( \frac{\Lambda_{Z_{t+1}} \Phi_{Q_t}}{\Phi_{Z_{t+1}}} + \frac{\Lambda_{Q_{t+1}} \Psi_{Q_t}}{\Psi_{Q_{t+1}}} - \Lambda_{Q_t} \right)}{(\Lambda_{Z_{t+1}} \Phi_{M_{t+1}} - \Lambda_{M_{t+1}} \Phi_{Z_{t+1}})}, \\
a_{22} &= \frac{-\Phi_{Z_{t+1}} \left( \frac{\Lambda_{Z_{t+1}} \Phi_{M_t}}{\Phi_{Z_{t+1}}} + \frac{\Lambda_{Q_{t+1}} \Psi_{M_t}}{\Psi_{Q_{t+1}}} - \Lambda_{M_t} \right)}{(\Lambda_{Z_{t+1}} \Phi_{M_{t+1}} - \Lambda_{M_{t+1}} \Phi_{Z_{t+1}})}, \\
a_{23} &= \frac{-\Phi_{Z_{t+1}} \left( \frac{\Lambda_{Z_{t+1}} \Phi_{Z_t}}{\Phi_{Z_{t+1}}} + \frac{\Lambda_{Q_{t+1}} \Psi_{Z_t}}{\Psi_{Q_{t+1}}} - \Lambda_{Z_t} \right)}{(\Lambda_{Z_{t+1}} \Phi_{M_{t+1}} - \Lambda_{M_{t+1}} \Phi_{Z_{t+1}})}, \\
a_{31} &= \frac{\Phi_{M_{t+1}} \left( \frac{\Lambda_{M_{t+1}} \Phi_{Q_t}}{\Phi_{M_{t+1}}} + \frac{\Lambda_{Q_{t+1}} \Psi_{Q_t}}{\Psi_{Q_{t+1}}} - \Lambda_{Q_t} \right)}{(\Lambda_{Z_{t+1}} \Phi_{M_{t+1}} - \Lambda_{M_{t+1}} \Phi_{Z_{t+1}})}, \\
a_{32} &= \frac{\Phi_{M_{t+1}} \left( \frac{\Lambda_{M_{t+1}} \Phi_{M_t}}{\Phi_{M_{t+1}}} + \frac{\Lambda_{Q_{t+1}} \Psi_{M_t}}{\Psi_{Q_{t+1}}} - \Lambda_{M_t} \right)}{(\Lambda_{Z_{t+1}} \Phi_{M_{t+1}} - \Lambda_{M_{t+1}} \Phi_{Z_{t+1}})}
\end{aligned}$$

and

$$a_{33} = \frac{\Phi_{M_{t+1}} \left( \frac{\Lambda_{M_{t+1}} \Phi_{Z_t}}{\Phi_{M_{t+1}}} + \frac{\Lambda_{Q_{t+1}} \Psi_{Z_t}}{\Psi_{Q_{t+1}}} - \Lambda_{Z_t} \right)}{(\Lambda_{Z_{t+1}} \Phi_{M_{t+1}} - \Lambda_{M_{t+1}} \Phi_{Z_{t+1}})}$$

(notice that all derivatives must be evaluated at  $(Q^\circ > 0, M^\circ > 0, Z^\circ > 0)$ ).

As a numerical example, let  $H=0.5633265$ ;  $g=0.2$ ;  $\alpha=\beta=\phi=\xi=0.5$ ;  $\delta=0.1$ ;  $\gamma=0.8$ ;  $\eta=0.4$ ;  $\mu=1/3$ ;  $\theta=0.95$ . Given these parameter values, one has  $Q^\circ=2.3524842$ ;  $M^\circ=Z^\circ=0.0403328$ ;  $L^\circ=0.4109$ ;  $\rho^\circ=0.0300222$ . In this case, the characteristic equation of the linearized system is  $\omega^3 - 3.0969667\omega^2 + 3.1290874\omega - 1.0367497=0$ , thus giving  $\omega_1=0.88996707$ ;  $\omega_2=0.87375770$ ;  $\omega_3=1.33324192$ . The fact that  $0 < \omega_1 < 1$ ,  $0 < \omega_2 < 1$  and

$\omega_3 > 1$  implies that  $(Q^\circ > 0, M^\circ > 0, Z^\circ > 0)$  is saddle-path stable, since  $Z_0 = \frac{K_{V0}}{K_{T0}} M_0$ , while  $Q_0$  and  $\frac{K_{V0}}{K_{T0}}$  are given.

## 7.5 Proof that $L^\circ$ is Monotonically Increasing in $\varphi$ and Monotonically Decreasing in $\xi$

Given (A22) and the fact that  $\tilde{L} < L^\circ < H$ , one has

$$\left. \frac{\partial l(L, \varphi, \xi)}{\partial L} \right|_{L=L^\circ} > 0. \quad (\text{A24})$$

It is also easy to check that

$$\left. \frac{\partial l(L, \varphi, \xi)}{\partial \varphi} \right|_{L=L^\circ} < 0 \quad (\text{A25})$$

and

$$\left. \frac{\partial l(L, \varphi, \xi)}{\partial \xi} \right|_{L=L^\circ} > 0. \quad (\text{A26})$$

Invoking the implicit function theorem, (A24), (A25) and (A26) prove that  $L^\circ$  is monotonically increasing in  $\varphi$  and monotonically decreasing in  $\xi$ .

## 7.6 Derivation of Equation (33)

Given (6), (7) and (A7), one has that along an equilibrium path

$$T_t = K_{Tt} \left[ \frac{\xi(1-\gamma)}{(1-\xi)(1-\eta)} \right]^\gamma M_t^{\frac{1-\gamma}{\gamma}} \frac{\eta(1-\gamma)}{\gamma} \quad (\text{A27})$$

and

$$V_t = K_{Tt} Z_t M_t^{-\eta}. \quad (\text{A28})$$

By using (A27) and (A28) to substitute, respectively, for  $T_t$  and for  $V_t$  in (32), one can obtain

$$R_{t+1} - R_t = \lambda R_t \left\{ 1 - \frac{N_t}{\nu M_t^\eta} \left[ \zeta \left[ \frac{\xi(1-\gamma)}{(1-\xi)(1-\eta)} \right]^\gamma M_t^{\frac{1-\gamma}{\gamma}} + (1-\zeta) Z_t \right] \right\}, \quad N_t \equiv R_t K_{Tt}$$

By multiplying both sides of this equation by  $K_{Tt}$ , one obtains (33).

## 7.7 Derivation of Equation (35)

By using (30), (A11), (A27) and (A28), one can obtain the

households' period utility along the BGP:

$$\begin{aligned}
u_{t+i}^{\circ} = & (1 + \alpha - \kappa) \ln(K_{T_{t+i}}) + \ln \left\{ \left[ \frac{\xi(1-\gamma)}{(1-\xi)(1-\eta)} \right]^{\frac{1}{\gamma}} (M^{\circ})^{\frac{\eta}{\gamma}} + \frac{(1-\gamma)}{(1-\eta)} Z^{\circ} \right\} - \\
& - \ln[\alpha(1-\gamma)] + \beta \ln(H - L^{\circ}) - \alpha \eta \ln(M^{\circ}) + \\
& + \alpha \ln \left\{ \xi \left[ \frac{\xi(1-\gamma)}{(1-\xi)(1-\eta)} \right]^{\frac{1-\gamma}{\gamma}} (M^{\circ})^{\frac{\eta}{\gamma}} + (1-\xi) Z^{\circ} \right\} + \kappa \ln(N^{\circ}).
\end{aligned} \tag{A29}$$

By considering that along the BGP one has  $K_{T_{t+i}} = K_{T_t}(1+\rho^{\circ})^i$ , one can use (A29) to obtain (35).

## 7.8 Proof of Proposition 2

By inspecting (35), one can verify that  $\frac{\partial \left[ \frac{\ln(N^{\circ})}{(1-\theta)} - \frac{\theta \ln(1+\rho^{\circ})}{(1-\theta)^2} \right]}{\partial \varphi} < 0$

implies that for large enough values of  $\kappa$  (households' preferences attach a relatively large importance to the environment) one has

$$\frac{\partial \sum_{i=0}^{\infty} \theta^i u_{t+i}^{\circ}}{\partial \varphi} < 0.$$

To show that  $(1+\rho^{\circ})(1+\chi)\theta \geq 1$  is sufficient for having

$\frac{\partial \left[ \frac{\ln(N^{\circ})}{(1-\theta)} - \frac{\theta \ln(1+\rho^{\circ})}{(1-\theta)^2} \right]}{\partial \varphi} < 0$ , consider that (26) and (34) allow us to write

$$\begin{aligned}
& \frac{\ln(N^\circ)}{(1-\theta)} - \frac{\theta \ln(1+\rho^\circ)}{(1-\theta)^2} = \\
& \frac{\left\{ \ln \left[ \frac{\rho^\circ}{(1+\rho^\circ)\chi} + 1 \right] + \ln(v) + \eta \ln(M^\circ) - \ln \left[ \zeta \left[ \frac{\xi(1-\gamma)}{(1-\xi)(1-\eta)} \right]^{\frac{1-\gamma}{\gamma}} (M^\circ)^{\frac{\eta}{\gamma}} + \frac{\varphi(1-\zeta)M^\circ}{(1-\varphi)} \right] \right\}}{(1-\theta)} \\
& - \frac{\theta \ln(1+\rho^\circ)}{(1-\theta)^2} = \frac{\ln[\rho^\circ(1+\chi) + \chi] - \ln(\chi)}{(1-\theta)} - \frac{\ln(1+\rho^\circ)}{(1-\theta)^2} + \\
& + \frac{1}{(1-\theta)} \left\{ \ln(v) + \eta \ln(M^\circ) - \ln \left[ \zeta \left[ \frac{\xi(1-\gamma)}{(1-\xi)(1-\eta)} \right]^{\frac{1-\gamma}{\gamma}} (M^\circ)^{\frac{\eta}{\gamma}} + \frac{\varphi(1-\zeta)M^\circ}{(1-\varphi)} \right] \right\}.
\end{aligned} \tag{A30}$$

By considering Proposition 1 (stating that  $\rho^\circ$  increases with  $\varphi$ ), one can verify that  $(1+\rho^\circ)(1+\chi)\theta \geq 1$  entails

$$\frac{\partial \frac{\ln[\rho^\circ(1+\chi) + \chi] - \ln(\chi)}{(1-\theta)} - \frac{\ln(1+\rho^\circ)}{(1-\theta)^2}}{\partial \varphi} \leq 0. \tag{A31}$$

Moreover, by considering (A21), (A24) and (A25) ( $M^\circ$  increases with  $L^\circ$ , which in its turn increases with  $\varphi$ ), one can verify that

$$\frac{\partial \frac{1}{(1-\theta)} \left\{ \ln(v) + \eta \ln(M^\circ) - \ln \left[ \zeta \left[ \frac{\xi(1-\gamma)}{(1-\xi)(1-\eta)} \right]^{\frac{1-\gamma}{\gamma}} (M^\circ)^{\frac{\eta}{\gamma}} + \frac{\varphi(1-\zeta)M^\circ}{(1-\varphi)} \right] \right\}}{\partial \varphi} < 0 \tag{A32}$$

Thus, (A30), (A31) and (A32) show that  $(1+\rho^\circ)(1+\chi)\theta \geq 1$  is

sufficient for having  $\frac{\partial \sum_{i=0}^{\infty} \theta^i u_{t+i}^\circ}{\partial \varphi} < 0$  in the presence of large enough values of  $\kappa$ .

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