Transport Policy 49 (2016) 226–233

Contents lists available at ScienceDirect

Transport Policy

journal homepage: www.elsevier.com/locate/tranpol

Instability and dynamic cost elasticities in freight transport systems

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ARTICLE INFO

Article history:
Received 9 November 2015
Received in revised form
3 May 2016
Accepted 9 May 2016
Available online 19 May 2016

Keywords:
Freight transport
Dynamic cost functions
Fixed points
Freight transport instability
Dynamic cost elasticities

ABSTRACT

The paper studies two properties of freight transport systems with dynamic cost functions. The first property is that the dynamic cost functions can give rise to situations in which the transport system is unstable. This property has a number of consequences. One of them – important from a practical point of view – is that, if a transport mode implements a plan of improvements of its characteristics in order to stop the decline of the proportion of freight flow it carries, there is a time threshold to start the improvements, beyond which the plan is unsuccessful. The other property is that the dynamic cost functions give rise to cost elasticities that vary over time, with asymptotic values that tend to zero as transport cost decreases. This means that, if one implements successive improvements of the characteristics of a transport mode, their effects diminish progressively.

1. Introduction

Consider two territories between which there is exchange of freight carried by n transport modes, where we mean by transport mode a solution to transfer freight from an origin to a destination, which uses a particular set of technologies, of organizational structures and of itineraries, in a given environment. As supposed in Ferrari (2014, 2015), a carrier, who sends regularly goods between these two territories, in order to choose the transport mode that he deems the best, arranges all the alternative modes in a set, and assigns to each of them a number, named *transport cost*: the higher the cost is, the less preferable the alternative is. Transport cost for each mode is a random variable, whose average varies over time as a consequence of congestion due to the increase in freight flow carried by the mode, and as an effect of modifications in technology and organizational structures. The increase in freight flow causes on one hand an increase in cost due to the increase in congestion. On the other hand the increase in freight flow due to the improvements in technology and organizational structures represents a stimulus to further improvements, and thus to further cost decreases, whereas a progressive reduction in freight flow, in spite of technological and organizational efforts, causes a decrease in efforts, with an increase in transport cost. Thus, while the component of the average transport cost due to congestion is an increasing function of freight flow, that depending on the modifications in technology and organizational structures is a decreasing function of freight flow. We define as *dynamic cost function* of a transport mode the relation between average transport cost and freight flow. It can be increasing or decreasing, depending on which cost component prevails over the other.

This type of cost functions are different from those used by many authors for studying the freight transport modal split in different situations (see e.g. Cascetta, 2001; Chow et al., 2010; de Joung and Ben-Akiva, 2007; Janic, 2007; Masiero and Rose, 2013; Norojono and Joung, 2003; Nuzzolo and Russo, 1995; Winston, 1983). Indeed they are static, i. e. they furnish the cost corresponding to given attributes of both the production and transport systems. When they are used in models to forecast modifications in the distribution of the overall freight flow among the various transport modes due to changes in some attributes, they suppose that these attributes after the changes remain constant over time. Instead this paper supposes that transport cost is a function of freight flow f and of a vector z of attributes, which vary over time as a function of f, $z = z(f)$, due to the changes in technology and organizational structure of the transport modes, which accompany the evolution of flow, as said before. Thus transport cost c is a composite function of flow: $c(f) = \phi[f, z(f)]$. The interactions between changes in flows and in technological and organizational characteristics give rise to different cost functions, and thus to different evolutions over time of modal split. The pattern of this evolution during a time period can be used to estimate the parameters of the dynamic cost functions, as said in Ferrari (2014).

In a freight transport system, constituted by n transport modes, some dynamic cost functions can be increasing, while the others are decreasing. The life of this transport system is constituted by a sequence of time periods characterized by different modal split evolutions: at the beginning of each period there is the change in the dynamic cost functions of some transport modes. This change can be due to the introduction of a new infrastructure, causing a

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http://dx.doi.org/10.1016/j.tranpol.2016.05.008

modification of the increasing relation between transport cost and freight flow; or it can be the consequence of modifications in the way with which technology and organization of a transport mode evolve over time – as a response to the evolution of freight flow – causing a modification in the decreasing relation between transport cost and freight flow.

An important consequence of the dynamic cost functions is that they can give rise to situations in which the transport system is unstable, because small variations in the characteristics of the system cause substantially different evolutions over time. This problem will be analyzed in the paper from a theoretical point of view, and will be studied in a real case with reference to the evolution – during a time period – of the modal split of a transport system one mode of which suffered, in the previous period, a decrease over time in the proportion of the freight flow it carries. At the beginning of the new period this mode decided to implement a plan to stop this decrease and to recover at least in part the lost proportion of traffic by improving technology and organization. We will show that there are situations in which very little changes in the parameters of the transport system can cause success or the failure of the plan.

Another important consequence of the dynamic cost functions is that they give rise to a new view on cost elasticities for freight transport. According to de Jong (2013), "elasticity gives the impact of a change in an independent variable on a dependent one, both measured in percentage change". In this paper we will consider the dynamic cost functions as independent variables that are modified, and the modal split as dependent variable. It will be shown that elasticities for the modes of a transport system with dynamic cost functions evolve over time, tending to asymptotic values – the long term dynamic elasticities – which decrease as transport cost decreases.

The paper is organized in this way. Section 2 is dedicated to the study of the characteristics of a freight transport system that make it unstable. Section 3 presents a study of the instability concerning the transport system between North-Western Italy and Central-Northern Europe. Section 4 analyses the properties of the elasticities of a freight transport system with dynamic cost functions. Lastly, a brief summary of the main points is presented and some conclusions are put forward in Section 5.

2. Instability of freight transport systems with dynamic cost functions

Consider two rather large territories, between which there is exchange of freight carried by n transport modes in competition with each other. The behaviour of this transport system is studied during a sequence Σ of unit time intervals (e.g. one year), in a time period during which the dynamic cost functions of the transport modes do not change. Let T^t be the amount of freight (measured e.g. in million tons) exchanged in both directions between the two territories in one unit time at time t, and carried as a whole by the n transport modes. T^t, which is named *freight flow* between the two territories, increases over time at rate r^t, tending to an asymptotic value K. Rate r^t decreases as T^t increases and tends to zero when T^t approaches K. By denoting $\bar{r}$ as the starting value of r^t, corresponding to zero freight flow, the equation determining the evolution over time of T^t is:

$$T^{t+1} = T^t\left[1 + \bar{r}\left(1 - \frac{T^t}{K}\right)\right] \tag{1}$$

By denoting x_i^t as the proportion of T^t that uses mode i, the freight flow of mode i at time t is expressed by $x_i^tT^t$.

As we have seen in Section 1, the model supposes that a carrier, who intends to send freight between two points in the two territories, assigns a number – named *transport cost* per transport unit – to each transport mode: the higher the cost is, the less preferable the mode is. Transport cost is a random variable, whose mean – as said in Section 1 – is a function $c_i(x_i^tT^t)$ of freight flow $x_i^tT^t$ that uses mode i in the successive times of sequence Σ. Function $c_i(x_i^tT^t)$, which can be increasing or decreasing, is named *dynamic cost function*.

The model supposes that a user assigns to each mode a cost at time $t+1$ on the basis of his knowledge of the performance of the mode at time t, and thus that the average cost assigned to mode i at time $t+1$ is a function of freight flow $x_i^tT^t$. Assuming this hypothesis, and supposing that transport costs are Gumbel random variables identically and independently distributed, is has been proved in Ferrari (2014) that the fraction $\bar{x}_i^t$ of T^{t+1} that would use mode i at time $t+1$, if each user chose the transport mode to which he assigned the minimum cost, is given by:

$$\bar{x}_i^t = \frac{\exp\left[-c_i(x_i^tT^t)\right]}{\sum_{j=1}^{n}\exp\left[-c_j(x_j^tT^t)\right]} \quad \forall\, i \in (1, \ldots, n) \tag{2}$$

For the reasons explained in Ferrari (2014), users shift with a certain delay from a transport mode to another deemed more suitable. Because of this delay, only some of those who deem mode i better than that they are using at time t will abandon the latter at time $t+1$. This means that $x_i^{t+1} - x_i^t$ is only a fraction of $\bar{x}_i^t - x_i^t$, so we have:

$$x_i^{t+1} = x_i^t + \beta\left[\bar{x}_i^t - x_i^t\right] \quad \forall\, i \in (1, \ldots, n) \tag{3}$$

where parameter β, $0 < \beta < 1$, which the model supposes to be constant, is the ratio of the difference $x_i^{t+1} - x_i^t$ between the proportions of users of mode i at times $t+1$ and t, to the difference $\bar{x}_i^t - x_i^t$ of the proportion that would occur if all users chose at time $t+1$ the mode that they deem the best. Thus it is a measure of the delay with which users shift from a mode to another: the slower users are, the smaller β is.

We suppose that the dynamic cost functions of modes $i = 1, 2, \ldots, m$ are decreasing exponential functions of freight flow $T_i^t = x_i^tT^t$:

$$c_i(x_i^tT^t) = a_{i,1} + a_{i,2}\exp(-a_{i,3}x_i^tT^t) \quad i = 1, 2, \ldots, m \tag{4}$$

while the dynamic cost functions of the other modes $i = m+1, \ldots, n$, are increasing second order polynomial functions of $T_i^t = x_i^tT^t$:

$$c_i(x_i^tT^t) = a_{i,1} + a_{i,2}x_i^tT^t + a_{i,3}(x_i^tT^t)^2 \quad i = m+1, \ldots, n \tag{5}$$

The validity of the choice of these expressions for the cost functions will be verified in Section 3 through the study of a real case.

By denoting $\mathbf{x}^t$ as the vector whose components are x_i^t, $i = 1, \ldots, n$, given the initial vector $\mathbf{x}^0$ and the initial value T^0 of T^t, the sequence $\left\{\mathbf{x}^t\right\}$ of vectors $\mathbf{x}^t$ is computed, by taking into account Eq. (3), by iterated application of the equation:

$$\mathbf{x}^{t+1} = \mathbf{x}^t + \beta\left[\bar{\mathbf{x}}^t(\mathbf{x}^tT^t) - \mathbf{x}^t\right] \tag{6}$$

where $\bar{\mathbf{x}}^t(\mathbf{x}^tT^t)$ is the vector whose components are given by Eq. (2), while the sequence of T^t values are generated by iterated application of Eq. (1) starting with T^0. If the sequence $\left\{\mathbf{x}^t\right\}$ converges towards an equilibrium point, this is a fixed point $\mathbf{x}^*$ of Eq. (6) when T^t assumes the asymptotic value K. By denoting $\bar{\mathbf{x}}(K\mathbf{x}^*)$ as the vector whose components are given by Eq. (2) when $T^t = K$ and $x_i^t = x_i^*$, $i = 1, \ldots, n$, and putting $\mathbf{x}^{t+1} = \mathbf{x}^t = \mathbf{x}^*$ and $T^t = K$ in Eq. (6), we have: