Modeling Transport Pricing with Multiple Stakeholders

Working Paper: Methodology and a Case Study

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Abstract

Pricing measures (e.g., a kilometre charge or cordon toll) are used to improve the external effects of transportation (e.g., congestion or emissions). This working paper presents a planning model for pricing while taking the preferences and interactions of multiple stakeholders (e.g., governments or public transport operators) into account. Because we do not restrict ourselves to a single stakeholder, the model can analyse the interdependencies between measures and, particularly, the positive effects of cooperation between stakeholders. The presented model framework uses game theory for the interaction of stakeholders, who each have an objective function and control some pricing measure. Two concepts are considered, which both result in different pricing strategies. The first is non-cooperation which assumes selfish behaviour; we defined the stakeholder equilibrium to determine the solution strategy. Second, the cooperative solution concept allows coalitions to be formed; we developed a transferable utility game with its corresponding core to determine stable solution strategies. The model is tested on a stylised case study with travellers between three cities in which the government implements a kilometre charge on the road and the railway operator changes the train fares. Analysis of the different concepts showed that cooperation between the government and railway operator results in different and better pricing strategies. So, our model can analyse the benefits of cooperation in a transport system; furthermore, it can identify the coalitions and corresponding pricing strategies needed to achieve these benefits.

Keywords

Transport pricing, multiple stakeholders, game theory, cooperative and non-cooperative solutions

1 Introduction

Congestion and emissions are examples of the external effects of transport that can be reduced with pricing. Transport pricing continues to be discussed and implemented; its main goal is to improve the transport system. Pricing incentives are effective since they can change travellers' choices (e.g., mode, route and departure time choice). Changes in travel behaviour will affect the transport network performance, which in turn will lead to different levels of external effects. Stakeholders can adjust the pricing strategy to obtain travel behaviour that minimizes the external effects.

Pricing schemes are designed, evaluated and assessed with planning models. Such a model captures the behaviour of travellers (i.e., travel choices) and stakeholders (i.e., price determination); furthermore, the model addresses the impact of these choices on the transport network. A regular planning model for example tries to minimize the vehicle loss hours (i.e, congestion) by varying the toll price. The available knowledge regarding the behavioural response of travellers is abundant and settled in literature. This also holds for determining the succeeding effects, for which traffic assignment models are available. So the established *transport models* allow the assessment of a *pricing scheme* (i.e., price level) and result in quantified *effects* (e.g., degree of congestion, emission levels). Stakeholders on the other hand have to determine the pricing scheme that results in the desired effects.

The classical approach models stakeholder behaviour as an optimization problem. First, an objective function is defined that rates the effects. Second, an optimization methodology is applied to determine which pricing scheme will result in optimal effects. The transport model functions here as an equilibrium constraint. This classical approach is very straightforward. Of course this is a highly non-linear problem and numerous runs of the transport model are required; nevertheless, it remains restricted to a single objective function. However, in reality multiple stakeholders are present, and they have different preferences and interaction. In fact, the implementation of pricing measures in the Netherlands has failed because of conflicts between stakeholders; in this case the negative opinion of the Royal Dutch Touring Association (ANWB) caused the government to abort the project. The interactions and conflicts can not be captured by a single objective function; therefore, the currently used methods are not sufficient to model stakeholder behavior. No model exists that can take the different preferences and interactions of stakeholders into account.

This study is the first to model stakeholder behaviour by identifying all stakeholders and their preferences. Each stakeholder rates the effects differently and therefore has its own objective function. Furthermore each pricing measure is controlled by exactly one stakeholder. This results in a system of optimization problems. These problems are connected by the underlying transport model since the travellers will not respond to each individual price, but on the combination of prices. Since there is more than one objective function – which is constrained by the common transport model – the problem can not be stated as an optimization problem. However, game theory provides methods to determine the resulting pricing scheme for different levels of interaction. Basically, the stakeholders can either cooperate or not, which leads to very different pricing schemes, transport system performance, and effects. This paper shows how to take the behaviour of multiple stakeholders into account in planning models for pricing measures.

Two game theoretical approaches are discussed. First, non-cooperation does not allow communication between stakeholders and assumes selfish behaviour of each stakeholder. The non-cooperative solution is based on the notion of equilibrium, if no stakeholder can unilaterally improve its price, then Nash equilibrium is reached. Second, cooperation can lead to coalitions between stakeholders and allows monetary transfers between stakeholders. Cooperative solution concepts are derived from the transferable utility (TU)-game framework.

The cooperative and non-cooperative approaches are demonstrated with a synthetic case study of three cities. The inter-city travel is considered and the travellers can choose between car and train. There are two stakeholders, the government and the railway operator. The government introduces a kilometre charge on the main corridor to mitigate congestion. The railway operator can change the fares to optimize their profit. The pricing schemes in this system depend strongly on the level of cooperation. Moreover, the cooperative solution results in a better transport system.

2 Stakeholders Model Framework

2.1 Introduction

This section presents a model framework to analyse the preferences and interactions of stakeholders in a transport pricing setting. The stakeholders try to influence the transport system for the benefit of their own preference by controlling their own pricing measure. The transport model, which relates the price levels with the external effects, is exogenous and serves as a constraint. Interactions between stakeholders are captured with game theory. The non-cooperative case and the cooperative case are identified; for the first a stakeholder equilibrium is defined and for the second a transferable utility game (TU-game) is developed.

2.2 Model definitions

This section presents a framework that can be design and evaluate pricing schemes in a multiple stakeholder setting. The general framework can be used to develop planning models for transport pricing in settings with conflicting interests or in settings where multiple pricing measures are present.

The stakeholders have to determine the price level for each pricing measure; denote n as the total number of price levels of all measures. This price level is represented by price vector $\boldsymbol{p} = (p_1, \ldots, p_n) \in P \subseteq \mathbb{R}^n$, where P is the set of feasible prices. Some pricing measures are represented by more than one element in $\boldsymbol{p}$, for example, a parking tariff that has different prices three zones is represented by three elements in $\boldsymbol{p}$. The set of feasible prices P contains all combinations of price levels that can be implemented.

On the other hand, the stakeholders will set the prices such that the external effects are at their preferred levels; denote m as the total number of external effects. The external effect levels are represented by effects vector $\boldsymbol{e} = (e_1, \ldots, e_m) \in \mathbb{R}^m$. Examples of effects that can be contained in $\boldsymbol{e}$ are total loss hours (to quantify congestion) and total emissions.

Travellers will respond on pricing levels; they can change their mode, route and departure time. This behavioural response will in term lead to a change in traffic flows.

Afterwards, the change of travel flows will lead to other network performances and therefore travel times. Finally, the travellers will react on the changes in travel tima and an iterative process arises. This process is captured in Dynamic Traffic Assignment (DTA) models. This study uses a DTA model to find the user equilibrium under a certain price level $\boldsymbol{p}$ and results in an external effects level $\boldsymbol{e}$. Denote $\text{DTA}(\boldsymbol{p}) : \mathbb{R}^n \to \mathbb{R}^m$ as the operator that prices to the effects under user equilibrium. So, the transport model is captured in a simple operator and takes care of travel demand and network supply interactions.

Consider now a set of stakeholders S who all want to influence the transport system by setting prices. Each stakeholder $s \in S$ has its own preferences in terms of external effects which is represented by objective function $f_s : \mathbb{R}^m \to \mathbb{R}$. For this study it is assumed that $f_s(\boldsymbol{e})$ is monetized such that it represents the monetary gains of the stakeholder.[1] Each price element in $\boldsymbol{p}$ is controlled by one of the stakeholders; therefore, each stakeholder has its set of feasible set prices where it can choose from. The feasible set of prices for each stakeholder $s \in S$ is denoted by P_s, and $\boldsymbol{p}_s \in P_s$ denotes a price level vector for stakeholder s.[2]

Since there is more than one objective function, the behaviour of the stakeholders can not be represented with a simple optimization problem. However, an optimization problem for a single stakeholder could be set up if it is assumed that all other stakeholders keep their prices fixed. First, this simplified version is discussed before we take all stakeholders into account in Section 2.3. So, assume that all stakeholders except $s \in S$ have their prices fixes, denote these prices with $\bar{\boldsymbol{p}}_{S\setminus\{s\}}$. Then for stakeholder s the following problem formulation is defined:

$$\begin{aligned} \max_{\boldsymbol{p}_s \in P_s} \quad & f_s(\boldsymbol{e}) \\ \text{such that} \quad & \boldsymbol{e} = \text{DTA}\left(\boldsymbol{p}_s, \bar{\boldsymbol{p}}_{S\setminus\{s\}}\right) \end{aligned}$$

Classical planning models do have such an approach. They do not take the responses of other stakeholders into account and ignore possible interaction between stakeholders.

2.3 Solution Approaches

2.3.1 Non-cooperative

In the non-cooperative approach each stakeholder acts selfishly. This means that if they can change the price to improve their objective, they will do so. On the other hand, no communication between stakeholders exist; the price levels of each stakeholder is the only available information to act on. In the analysis of such a setting one can not say very much. The stakeholders will continue to change their price, if they find they can be better of. Such a process might converge to equilibrium and that is exactly what is presented here.

Definition 1 (Stakeholders Equilibrium)**.** *Prices $\boldsymbol{p}^* \in P$ are in* stakeholders equilibrium *if no $\boldsymbol{p} \in P$ exists such that for each stakeholder $s \in S$*

$$f_s(\boldsymbol{p}) > f_s(\boldsymbol{p}^*)$$

[1] This assumption can be released. In that case the relative preferences of all stakeholders are required to be able to compare the different values.

[2] Each price vector $\boldsymbol{p} \in P$ is represented by a combination of $\{\boldsymbol{p}_s, s \in S\}$. Thus the set of feasible prices P is the set product of stakeholder specific feasible price sets: $P = \prod_{s \in S} P_s$.

and

$$p_i = p_i^* \quad \forall i \in P \setminus P_s$$

In other words, the game is in stakeholders equilibrium of no stakeholder can unilaterally change its price to improve its objective.

2.3.2 Cooperative

The cooperative case does allow stakeholder to confer with each other and it is possible to form coalitions. Moreover, they are allowed to have monetary transfers. Compared to the non-cooperative case, the cooperative case much more interesting in a game theoretical perspective. This study takes a *transferable utility game* (TU-game) since this allows for monetary transfers and coalitions can be formed. Amongst other possible approaches is 'mechanism design', where the preferences (i.e., rankings of pricing levels) of multiple stakeholders are combined into a single preference. The disadvantage of this approach is that more than one mechanism can be considered and some player that acts on top of all others is introduced. The top level player has behaviour that is inherited from the chosen mechanism. The advantage of a TU-game is that it classifies each possible outcome of the game. The outcome is a set of pay-offs defining the final benefit of each stakeholder.

As mentioned above coalitions can be formed in TU-games; each coalition consists of a set of stakeholders and is denoted with $C \subseteq S$. S is a special coalition, called *grand coalition*, which includes all stakeholders. For each coalition a *value* $v(C)$ is defined which represents the total achievable utility if the stakeholders cooperated. For each coalition $C \subseteq S$ define

$$\begin{aligned} v(C) = \quad & \max_{\boldsymbol{p}_C \in \prod_{s \in C} P_s} && \sum_{s \in C} f_s(\boldsymbol{e}) \\ & \text{such that} && \boldsymbol{e} = \text{DTA}\left(\boldsymbol{p}_C, \bar{\boldsymbol{p}}_{S \setminus C}\right) \\ & && \bar{\boldsymbol{p}}_{S \setminus C} \text{ is in stakeholders equilibrium.} \end{aligned}$$

The value of the empty coalition equals zero since no stakeholder participates: $v(\emptyset) = 0$. Furthermore, denote that v is monotonic (i.e., if you add a stakeholder to the coalition, then v will increase).

A result of a TU-game is an allocation $x \in \mathrm{R}^S$ that represents the pay-offs to all stakeholders. This automatically captures all monetary transfers because each stakeholder $s \in S$ pays or receives the difference between $f_s(\boldsymbol{e})$ and x_s. As known in the TU-game literature, the *core* consists of all allocations that have some basic properties. These properties are:

- Efficiency: (all achieved utility is allocated)

$$\sum_{s \in S} (x_s) = v(S)$$

- Individual rationality: (no stakeholder has an opt out incentive)

$$x_s \geq v(\{s\}) \qquad \forall s \in S$$

- Stability: (there is no incentive to kick a stakeholder out)

$$\sum_{s \in C} x_s \geq v(C) \qquad \forall C \subseteq S$$

The core now consists of all allocations x that meet these requirements.

3 Case Study: Kilometre charge and train fares

3.1 Introduction

This section presents the application of the stakeholders model framework on a stylized transport system. There are two stakeholders who act on the highway and rail road network between three cities. The government mitigates congestion on the highways by introducing a kilometre charge. On the other hand the train operator tries to maximize profit by altering ticket fares. Both the non-cooperative and the cooperative approach are investigated in this system. In line with expectations, the coalition of the government and train operator results in an improvement for both parties than compared to the stakeholders equilibrium.

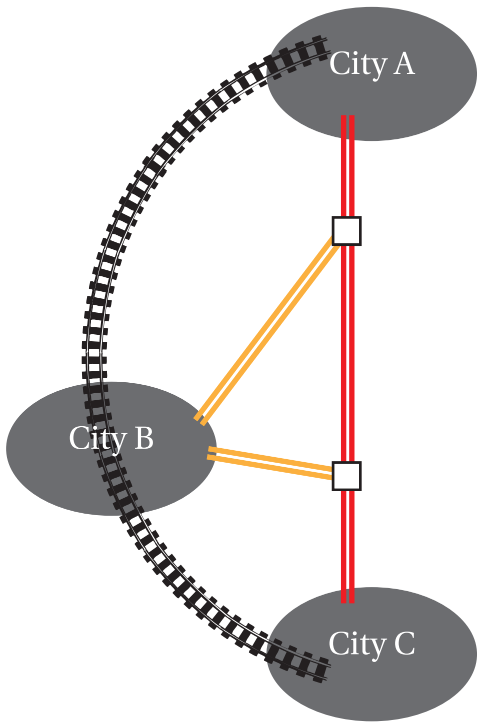

Figure 1: Network of three cities with connecting highways and rail road

Figure 1 shows the three cities and the connecting highways and rail road. On the red highway, connecting city A to city C directly, a kilometre charge can be implemented. The government has seven pricing regimes of which three are time-differentiated, i.e., they have an on-peak and off-peak tariff. The feasible prices for the government (P_{gov})

are given by

$$P_{\text{gov}} = \left\{ \begin{array}{l} (0;0) \\ (3;3) \\ (5;5) \\ (7;7) \\ (0;7) \\ (3;7) \\ (3;5) \end{array} \right\},$$

which is given in cents per kilometer in the form (off-peak; on-peak). The on-peak and off-peak periods are defined later when the transport model is discussed. Trains run between city A — city B — city C and vice versa. The train operator can change the ticket fares in the range -20% to +40% with steps of 10%. So, the feasible prices for the train operator (P_{train}) are given by

$$P_{\text{train}} = \left\{ \begin{array}{l} -20\% \\ -10\% \\ 0\% \\ +10\% \\ +20\% \\ +30\% \\ +40\% \end{array} \right\},$$

which is given in percentage in-/decrease with respect to current fare. This implies that feasible price set P contains 49 feasible prices, namely, the combinations of each kilometre tariff with each ticket fare.

There are two important external effects; first the total loss hours on the road network e_{loss} (i.e., the total delay experienced by all car drivers) and the profit of the train operator e_{profit}. The profit is calculated by subtracting the running costs of the trains from the total income of ticket sales. If the travel demand is high for a certain train, then the operator is obliged to add a service, which is rather costly. The objective function of the government equals $f_{\text{gov}} = -28.29e_{\text{loss}}$ (28.29 euro/hour is the value of time) and the objective function of the train operator equals $f_{\text{train}} = e_{\text{profit}}$.

Both stakeholders act on the transportation system; the optimization problem of the government is

$$\max_{p_{\text{gov}} \in P_{\text{gov}}} -28.29e_{\text{loss}},$$

and the optimization problem for the train operator is

$$\max_{p_{\text{train}} \in P_{\text{train}}} e_{\text{profit}}.$$

These problems, however, are constrained by the transport model, formulated as $(e_{\text{loss}}, e_{\text{profit}}) =$ DTA$(p_{\text{gov}}, p_{\text{train}})$, and this constraint is shared.

3.2 Transport model

The transport model consists of a discrete choice model and a dynamic network loading model. The discrete choice model simultaneously simulates mode, route and departure time choice. The dynamic network loading model uses the Link Transmission Model

		$\boldsymbol{p}_{\text{train}}$ -10%	0%	$+10\%$
	$(0;0)$	7,725/−2,898	0/0	−8,423/3,501
$\boldsymbol{p}_{\text{gov}}$	$(7;7)$	22,116/13,017	15,720/14,663	8,496/16,570
	$(0;7)$	23,095/4,886	17,770/5,183	12,116/7,912

Reduced loss hours/Increase of profit (both in Euro)

Table 1: Simulation results

for the highways because it produces realistic queue formation and uses a simple schedule based train model. When demand exceeds train capacity, an expensive additional service has to be introduced

3.3 Solutions

Table 1 shows the simulation results for the interesting pricing levels. Both the cooperative and non-cooperative results are discussed.

3.3.1 Non-cooperation

In this case study one stakeholders equilibrium exists at $\boldsymbol{p}^* = ((0;7), +10\%)$. At this point neither the government nor the train operator can improve its objective. So the government introduces a time differentiated kilometer charge of 7 cents on-peak and free off-peak, and the train operator increases the fares with 10 % under non-cooperation. Under this equilibrium the government earns 12,116 and the train operator earns 7,912. Next, the cooperative solution is investigated which gives an interesting result.

3.3.2 Cooperation

To determine the core of the corresponding TU-game, the value of each coalition has to be determined. The results for the two coalitions with a single stakeholder are equal to that of the non-cooperative case. For the coalition with both the government and the train operator, the following optimization problem has to be solved:

$$v(C) = \max_{\left(\boldsymbol{p}_{\text{gov}}, \boldsymbol{p}_{\text{train}}\right) \in P_{\text{gov}} \times P_{\text{train}}} \quad -28.29 e_{\text{loss}} + e_{\text{profit}}$$
$$\text{such that} \quad \left(e_{\text{loss}}, e_{\text{profit}}\right) = \text{DTA}\left(\boldsymbol{p}_{\text{gov}}, pp_{\text{train}}\right)$$

The solution of this problem is $\boldsymbol{p}^c = ((7;7), -10\%)$, so, the government introduces a fixed kilometre price of 7 cents and the rail operator decreases the fares with 10 % if they form a coalition. The earnings of both stakeholders are significantly higher as well. Namely 22,116 for the government and 13,017 for the train operator. This means that there is much less congestion and more profit under cooperation.

The core of this cooperative game consists is

$$\{(x_{\text{gov}}, x_{\text{train}}) | x_{\text{gov}} + x_{\text{train}} = 35.133,\ x_{\text{gov}} \geq 12.116, x_{\text{train}} \geq 7.912\}$$

4 Wrap up

This working paper presented a framework to model multiple stakeholders in transport pricing. The framework can take the preferences and interactions of stakeholders into account. Game theory is applied to investigate cooperative and non-cooperative solutions.

The framework is applied on a case study with a government that introduces a kilometre charge and a train operator that alters ticket fares. It is shown that if they communicate and form a coalition they are both better off. This shows that the model framework can be used in planning studies for transport pricing; especially, when multiple stakeholders with possibly conflicting preferences are present.

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