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A Game Theoretical Approach To Road Pricing With Multiple Stakeholders
A game theoretical approach to road pricing with multiple stakeholders

Master of Science Thesis

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Abstract

A game theoretic approach is used for examining road pricing with multiple stakeholders. The incorporation of users’ acceptance is modelled through the notion of a veto player. This approach and its value as a policy tool is examined through a case study of the extended Randstad area, with one user class and two stakeholders with different objectives and different road pricing measures they can control. The results show that through cooperation both stakeholders can achieve better results than in the non-cooperative case. The allocation of the gains from the cooperative case is done with the help of Shapley value. When incorporating users’ acceptance, both these solution are accepted. However, the Shapley value assigns less value to the other 2 stakeholders than when the veto player did not exist. Game theory is deemed beneficial for policy-making for road pricing, although extra attention should be paid not to oversimplify the interactions between the stakeholders when translating them from real life to mathematic terms of game theory.
Summary

Road pricing has been widely advocated as a measure to internalize external effects as well as an instrument for traffic management. The road pricing setting represents a hierarchical relationship between 2 decision levels, namely the decision-making authority setting the price in the upper level and the road users in the lower level. Users react on the decision authorities’ prices by changing their travel choices. However, in reality, there might be more than one stakeholder controlling different pricing measures, all of which affect the users’ choices.

This thesis examines the interaction between the stakeholders on the upper level and the outcomes that will be induced depending on whether these stakeholders cooperate or not before setting the price of their respective pricing measure, by employing a game theoretic approach. In addition to that, these solutions are examined under the scope of user acceptance, by employing the veto player theory. This game theoretic approach is then evaluated as a policy instrument. Furthermore, the effects of specific road pricing measures on the users’ travel choices and on the different objectives are examined.

For the scope of this analysis, a game theoretic approach is used. The stakeholders on the upper level have two choices, either to individually impose their price (non-cooperative case) and try to maximize their individual profit or to cooperate with each other (cooperative case) and try to maximize their combined profit, however without being left worse off. The games examined in this research are the Transferable Utility (TU) games, since it is possible to have side-payments from one stakeholder to another in order to induce cooperation. The two concepts of cooperative game theory that are examined are the core of the game and the Shapley value. The core of a game is the set of all stable outcomes, meaning all outcomes that no coalition or stakeholder wants to deviate from. Core solutions are the solutions that produce bigger gains for all stakeholders than in the non-cooperative case. The Shapley value is a concept for allocation of the gains generated from the formation of a coalition. Based on the Shapley value, each stakeholder receives his average marginal contribution that he brings to the coalitional gains. In the end, we use the veto player concept as to incorporate users’ acceptance in the upper level process (decision-making). A veto player in game theory is any player that if he/she is not part of a coalition, then this coalition is losing. The proposed reformulation of the upper level under this approach is shown below:
The aforementioned research is examined through a case study of the extended Randstad area. One user class is considered, the commuters, with the use of a static assignment model for two time periods, on-peak and off-peak. This model incorporates departure time choice and route choice. The decision authorities setting the pricing measures are the Municipality of Amsterdam, which imposes a cordon pricing around the city of Amsterdam, paid on entry and only on peak. The objective of the Municipality of Amsterdam is to minimize emissions on-peak. The second decision authority is the Dutch government, which is responsible for setting a kilometre charge on the highways on peak. The objective of the Dutch government is to minimize Total Travel Time on-peak. ANWB is representing the users, posing a veto for every solution that does not yield positive results for users’ surplus. There were 25 pricing scenarios modelled, one being the zero case, where no measure in employed and the rest 24 different combinations of the pricing measures.

It was observed that the non-cooperative and cooperative solutions were not the same, with the cooperative solution yielding better results in terms of a common objective, which simply is to maximize the gains of the sum of emissions and Total Travel Time, expressed in monetary terms. In non-cooperative case the objective of the government (Total Travel Time) improves €143 310, which means gains of 5.05% compared to the zero case, whereas the emissions improve by €49, yielding gains of 2.79%. In the cooperative case, the best joint outcome achieved is €145 575 in gains compared to the zero case, which results in better results for the Dutch government in terms of Total Travel Time gains (€145 536, meaning gains of 5.13%) but worse for the Municipality of Amsterdam in terms of emissions (€40 gains, improved by 2.29%, which is less than the 2.79% gains of the non-cooperative case). This means that this solution does not lie in the core, as explained in the theory before. It was also determined that both
these solutions were to be accepted from the ANWB, the users’ stakeholder, since the users’ surplus was in both cases positive.

<table>
<thead>
<tr>
<th>Pricing Scenario</th>
<th>TTT (in €)</th>
<th>Gains</th>
<th>Emissions (in €)</th>
<th>Gains</th>
<th>Accepted by ANWB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-Cooperative</td>
<td>Cordon pricing: € 4 3000 000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cooperative</td>
<td>Km Charge: € 0</td>
<td>2 695 655</td>
<td>5.05%</td>
<td>1 691</td>
<td>2.79%</td>
</tr>
<tr>
<td></td>
<td>Cordon pricing: € 2 3000 000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Km Charge: € 0</td>
<td>2 693 429</td>
<td>5.13%</td>
<td>1 700</td>
<td>2.29%</td>
</tr>
</tbody>
</table>

The Municipality of Amsterdam is left worse off and has to be compensated from the Dutch government which is left better off, at least until the amount of the non-cooperative case. When employing though the Shapley value, it turns out that the marginal contribution of the Municipality of Amsterdam (cordon pricing) on the overall objective is far bigger and that it should receive the amount of €118 554 from the total of €145 575 generated gains.

<table>
<thead>
<tr>
<th>Stakeholder</th>
<th>Marginal Contribution (in €)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Government</td>
<td>27 021</td>
</tr>
<tr>
<td>Municipality of Amsterdam</td>
<td>118 554</td>
</tr>
<tr>
<td>Total value added</td>
<td>145 575</td>
</tr>
</tbody>
</table>

In the case of incorporating users’ acceptance with the addition of ANWB in the game, the Shapley value allocates smaller portion of the gains to the Dutch Government and the Municipality of Rotterdam, since ANWB now gets an amount of the value generated.

<table>
<thead>
<tr>
<th>Stakeholder</th>
<th>Marginal Contribution (in €)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Government</td>
<td>739</td>
</tr>
<tr>
<td>Municipality of Amsterdam</td>
<td>72 418</td>
</tr>
<tr>
<td>ANWB</td>
<td>72 418</td>
</tr>
<tr>
<td>Total value added</td>
<td>145 575</td>
</tr>
</tbody>
</table>

The effect of kilometre charge was found to have a bigger influence on route choice than departure time choice, whereas cordon pricing yields minor effects. Kilometre charge was also found to affect Total Travel Time negatively in principal, as well as emissions in the city of...
Amsterdam. Cordon pricing has mixed effects on Total Travel Time and beneficial effects on decreasing emissions, although these effects are minor.

Table 4, Effects of road pricing measures on the objectives and users’ choices

<table>
<thead>
<tr>
<th>Km charge</th>
<th>Total Travel Time</th>
<th>Emissions</th>
<th>Route choice</th>
<th>Departure Time choice</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cordon pricing</td>
<td>Negative Effect</td>
<td>Negative effect</td>
<td>Big influence</td>
<td>Big influence, less than Route choice</td>
</tr>
<tr>
<td></td>
<td>Mixed effects</td>
<td>Positive effect</td>
<td>Minor influence</td>
<td>Minor influence</td>
</tr>
</tbody>
</table>

This research can be used from policy makers as an instrument for achieving broader social consensus regarding road pricing schemes, mainly before implementing them, so as to avoid delays during implementation and eventually underperformance of their respective objectives. It can also be employed as a tool for giving all stakeholders affected an insight of the effects each one has on the decisions of the others. In addition, this research can be used in decision-making to determine the need and the height of compensation for specific stakeholders. However, it might prove demanding to translate in mathematical terms these interactions between the stakeholders and to efficiently transform the objectives to mathematical terms, since each stakeholder values their objectives differently. For these games a large amount of information is needed from the stakeholders, to better map the game, which the stakeholders might not be willing to share. The veto player seems promising for capturing the effect of acceptance in the decision-making for road pricing, although it might assign more power to a stakeholder (the users in this case study) that might not possess.
Acknowledgements

This report concludes my studies for the MSc in Transport, Infrastructure and Logistics at TU Delft. The period of my studies was both happy and stressful. I choose to keep only the good memories and I would like to thank some people that are responsible for them.

First of all, I would like to thank my chairman, Prof. Dr. Ir Bart van Arem, for his guidance and support throughout my thesis research.

Secondly, I would like to express my sincere gratefulleness to Dr. Jan-Anne Annema, who as a supervisor offered me some very helpful advice on the long way of this thesis.

Last, but not least, I would like to thank Msc Erik-Sander Smits, who as my daily supervisor was helping me day after day, week after week, always being there, stuck with me without giving up on me. I really appreciate that.

I want to acknowledge all the people that I met throughout my study period in the Netherlands. They are too many and I am bound to forget somebody, so I will just say that I really, really thank you all.

I will just say a special thank you and I love you to Faidra and Antonia.

And of course, I want to thank my family for supporting me with every means.
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1. Introduction

Road pricing has been widely advocated as a measure to internalize external effects that are not taken into account by the users; those external effects include congestion, accident risk, noise, pollution, damage to the infrastructure. When users choose their route, they tend to take into account the time needed and the “out-of-the-pocket” costs (fuel, maintenance, tolls, fees etc). However, this way they neglect other costs that cannot usually be directly monetized and may even not be imposed on them, like including noise and emissions. By using road pricing, people will bear the full cost that they impose and therefore they will make more responsible choices.

The notion of road pricing was suggested as early as 1920, by Pigou in his work ‘The Economics of Welfare’. It should also be noted that it is one of the targets of European Union Transport policy, “to apply user charges to all vehicles and on the whole network to reflect at least the maintenance cost of infrastructure, congestion, air and noise pollution.” (European Commission, 2011).

Road pricing has also proven to be a good instrument for traffic management. Since users choose their route based on their individual cost, by imposing a fee, or by increasing an existing one, on one route or link, some users will reconsider their choice, and choose another route or link, thus leaving the tolled route with less congestion. However, there is no correct price, rather the correct or optimal price for each specific objective (Button, 1993).

The objective of a pricing scheme depends on the authority that sets the price. However, there may exist more than one stakeholder that owns the infrastructure, for example shared ownership of a network traversing several municipalities or countries, or even there may exist stakeholders or group of stakeholders that may not own the network or parts of it but their attitude toward the scheme is crucial for its correct implementation and success, for example residents around a pricing scheme or NGOs with significant power.

The road pricing setting represents a hierarchical relationship between 2 decision levels, namely the decision-making authority setting the price in the upper level and the road users in the lower level. With the use of game theory, this interaction can be represented by a Stackelberg game, a game where the leader makes a move (in this example a stakeholder that imposes the price) and the follower reacts accordingly (road users that choose a route). In this kind of game it is assumed that the leader can predict how the follower will react and can design his strategy accordingly (Fisk, 1984). In the lower level, users choose their route by pursuing the maximization of their personal welfare. An equilibrium of flows is reached when no user can increase his/her personal welfare by unilaterally change his route (according to Wardrop’s principles). This kind of interaction, between the users in the lower level, can be best modelled by a Nash non-cooperative game (Fisk, 1984).
However, this approach assumes that there is one leader. But what happens when more than one leader is present in the game?

1.1. Problem formulation

The above question takes us to the following problem formulation and the purpose of this research:

The traditional bi-level programs assume one decision-making authority. However this does not apply to realistic cases of today. **How can the traditional bi-level program for determining the price for road pricing measures be reformulated in order to include more than one stakeholder as decision-making authorities, as well as to include users in this decision process? What lessons can be learnt from this game theoretic approach for policy-making?**

This reformulation should include the options of stakeholders competing between them, as well as the case of them cooperating. The research will also examine the incorporation of users’ acceptance in the modelling framework, based on game theory. It should also be researched how different pricing instruments (like flat toll and km-charging) affect the model formulation and the stakeholders’ objectives.

1.2. Research questions

Main objective: Reformulation of the traditional bi-level program used for the road pricing problem to better fit in a multi-stakeholder environment (multi-leader multi-follower game) using game theory. In addition to that, exploration of how users’ acceptance can be incorporated in this bi-level game-theoretic formulation. Examination of whether game theory can be used in policy-making.

This objective will be researched by answering the following research questions:

1. Stakeholders and Road Pricing Theory
   - Why road pricing?
   - What examples of road pricing exist?
   - What lessons can be learnt?

2. Explorative Phase
   - How can the road pricing problem be represented (Bi-level formulation)?
   - What is the difference between one stakeholder and multiple stakeholders?
   - How can they interact with each other (competition or cooperation)-what is the game theory behind it?
   - How can user acceptance be incorporated using game theory tools?
   - What effects can be measured and how?

3. Case study
   Set-up
• Which case study - Which network to be chosen?
• What choices to be made for the lower level?
• Which stakeholders and objectives to be included in the upper level?
• What is needed (inputs and outputs) (data)?

Results
• What are the effects of the pricing measures on the users’ choices?
• What is the difference between the solutions for cooperation and competition between the stakeholders?
• Are these solutions accepted from the users?
• How can the gains be distributed to the stakeholders?
• What policy implication can be derived from these results

1.3. Research Approach

The aforementioned research questions have been categorized and included in the appropriate research phase. The phases that have been identified are 3, as shown in the Table 5 below: Phase 1 is the Stakeholders and Pricing theory, Phase 2 is the Explorative phase and Phase 3 is the Case study.

Table 5, Summary of Research Methodology and expected Results for each Research Phase

<table>
<thead>
<tr>
<th>Research Phase</th>
<th>Research methodology</th>
<th>Expected Results</th>
<th>Chapter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stakeholders and Pricing Theory</td>
<td>Literature review on road pricing-stakeholders-examination of pricing case studies</td>
<td>Identification of stakeholders that are usually involved, their objectives, importance of each objective, pricing measures that can be used</td>
<td>2</td>
</tr>
<tr>
<td>Explorative Phase</td>
<td>Literature review on game theory-modelling multi-stakeholders, bi-level transport modelling and especially for road pricing cases, modelling external costs and calculating effects</td>
<td>Commonly used game theoretic concepts, mathematical descriptions of the cooperative-non-cooperative game setups, effects measured and how, conceptual reformulation of the bi-level road pricing problem to incorporate game theory and user acceptance</td>
<td>3</td>
</tr>
<tr>
<td>Case Study</td>
<td>Case study set up and analysis of the Results with the use of OmniTrans</td>
<td>Model itself (building-testing-validation), results, analysis of the results regarding effect of pricing measures on users’ choices, analysis of game theoretic solutions, Policy implications</td>
<td>4-5-6</td>
</tr>
</tbody>
</table>
2. Road Pricing Schemes

For the design of a pricing scheme 3 particular aspects need to be determined: The pricing measure that will be applied, the objective that each scheme tries to accomplish and the stakeholders involved. These three aspects are presented and analysed in this chapter. Before this, the economic theory behind road pricing is briefly introduced. In the end of the chapter, existing international road pricing schemes are examined and conclusions are drawn regarding the main objectives that are mainly pursued, the road pricing measures that are used for this goal and what network effects have been observed regarding the travellers choices

2.1. Economic theory behind road pricing

Road pricing has been examined as an economic tool for internalizing external costs of transport (for example, and not limited to, in Button, 1993; Hau, 1992; Rouwendal and Verhoef, 2006 and Tsekeris and Voß, 2008). The foundations of the use of road pricing as a measure for internalizing the extra costs of congestion that each user imposes to the other drivers dates back to 1920 in the work of Pigou and in 1924 in the work of Knight (as stated in Rouwendal and Verhoef, 2006). The basic idea is that road users usually are not aware of the full costs that impose when they decide to make a trip or they may not care about it. For example, users usually tend to consider out-of-the-pocket costs such as fuel, car maintenance and taxes but tend not to consider the costs they impose to other users or external parties such as congestion, emissions and noise (Button, 1993). The latter are called external costs and for the case of road transport are briefly explained below (information taken from Santos, Behrendt, Maconi, Shirvani, & Teytelboym, 2010; CEDelft, Infras, & FraunhoferISI, 2011 and Wismans, 2012):

**Congestion:** When a new user enters the road, he/she interferes with the rest of the users. This consequently causes the users to lower their speed and therefore increases their travel time. However, when a user enters a road is usually not aware of this infliction in others. A high level of congestion (depending on the capacity of the road) can have several impacts on environmental, noise and accident levels except for time costs.

**Emissions:** Each vehicle produces emissions according to its fuel consumption, travelling speed, engine type etc. Users may not be aware of the damage imposed from these emissions, since it is not very easy to compute, but they can be significant. These emissions include carbon dioxide (CO$_2$), carbon monoxide (CO), particulates (PM), nitrogen oxides (NO$_x$), volatile organic compound (VOCs), sulphur oxides (SO$_x$), methane (CH$_4$), road dust and toxic gases.
**Noise:** Traffic noise depends on the traffic speed, accelerations, the portion of heavy vehicles and motorcycles, engine types. The magnitude of this problem also depends on whether the road is close or not to residential area.

**Accident risk:** It is logical to assume that the more users are on the road, the more interference between them and consequently the bigger the accident risk. However, the higher the occupancy on the roads is, the lower are the speeds, which leads also to a decrease in the severity of accidents.

**Road pavement damage:** Each vehicle that uses the road stresses the pavement. Repeated stress leads to failure of the pavement. As a result the more vehicles are on the road, the quicker the damage of a road segment.

Road pricing can be a valuable tool for internalizing these costs by making users pay for them and consequently force them to take them into account when they make a decision regarding whether to travel, where and how (Button, 1993).

![Figure 2, Social vs Private costs (own design, based on Button, 1993)](image-url)
As can be seen in Figure 2, users may not be aware of the costs they inflict on others, they regard the cost of their trip as being lower than it actually is (C^o instead of the actual C^\). However, if users were aware of all the costs they inflict on the others (social-external costs), there would be less trips made (amount N' that correspond to cost level C' instead of N^o that correspond to cost level C^o). By posing a fee equal to the one shown in Figure 2 these costs would be internalized and therefore less trips, equal to the socially optimal N' would be made. The intersection of PC and SC curves with the transport demand curve represents the optimal amount of trips and the associated cost of trip for that specific amount. These intersections represent the equilibrium between the transport demand and transport supply (curves SC and PC).

2.2. Pricing Measures

Road pricing measures or road charges are direct charges levied for the use of roads. Road pricing has different forms which include area licensing, cordon/zone charging, distance-based charging, time based charging and congestion charging. These fees can be levied with different ways, such as toll collection, paper licensing, number-plate recognition or electronic fee collection.

The pricing measures can have several different attributes. These include (according to information gathered from (CURACAO, 2009; Van Amelsfort, 2009 and Solehmainen, 2011):

**The pricing type**

**Area pass:** The fee is charged for making trips in a specific area. Users must purchase a pass or permit to enter a specific area. This pass/permit may be specific for a particular vehicle type, or time of the day.

**Cordon/zone charging:** A specific area is set up, with a cordon around it (for example the city centre) and users are charged depending on how many crossings of the cordon they make.

**Point based charge:** Such a charge can be levied on specific points of the infrastructure. This toll can be applied to specific links of the infrastructure (which is the main difference from the 2 measures mentioned above, which are applied over an area).

**Distance-based charging (km charging):** The fee is collected based on the distance travelled in the network, on a specific route or in a specified area.

**The price levels**

The price charged is an important factor in the user’s decision. As it has been mentioned before, users tend to value more the out-of-the-pocket costs. The price is an important factor of the cost function. The price level, as well as the existence of cheaper alternatives can influence all
user choices, from route choice to even their decision to make the trip. Of course it also affects their mode, destination and time of departure choice, also combined with the other characteristics of the pricing measure (type, differentiations etc).

**The price differentiation**

All pricing schemes can differ by location, by time of day (peak or off-peak hours), vehicle types (engine type, cars, trucks, weight etc.) or user groups (residents, car-poolers, different income etc.). Based on the objectives pursued by the pricing authorities several combinations can be made. For example, if the objective is equity, there may be exemptions for low-income travellers, whereas if the objective is lower emissions, the differentiation may be based on engine types. As several objectives are usually pursued, several differentiations may be present. These differentiations affect the cost functions of the users, as well as the general assignment models used. For example the more differentiations are present, the more segmentation has to be made (Multi-User Classes), which can lead to quite complex modelling problems.

If the price is the same (has no differentiation) the charge is called flat, if the measure has differentiations (either on different time of day, different vehicles, user groups etc) predetermined and indifferent of the actual conditions it is called variable and if a measure is actually dependant on the conditions on a specific instance then it is called dynamic.

In addition to the abovementioned factors several factors also have to be determined before the implementation of a pricing scheme, for example the collection system. However, these factors will not be examined in this thesis.

**2.3.Objectives**

*Importance of setting objectives*

Since road pricing is a policy measure that is faced with wide public scepticism and opposition, it is crucial that the objectives set for each scheme are clearly demonstrated. In addition, a scheme can have several objectives. Each objective or mix of objectives can be better served by different schemes or measures (May, Coombe, & Travers, 1996). Both these reasons show the importance of clearly stating the objectives of a road pricing scheme (CURACAO, 2009).

Objectives can be either expressed as vaguely as desired end points (cleaner air, improved mobility etc) or as problems that need to be overcome (casualties, congestion etc). These objectives depend on the stakeholders’ agenda, their power and of course their area of interest.

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1 This section draws information from the CURACAO project (Coordination of Urban RoAd-user ChArging), and more specifically from the report CURACAO (2009), “Deliverable D2: State of the Art Review” Project: Coordination of Urban Road User Charging Organisational Issues Sponsored by European Commission under the FP6 Framework
For example, an environmental agency would be more concerned and pursue goals such as lower emissions or better environment in general, but may not have the power needed to impose this agenda on stakeholders that have the power to do so, such as the government.

Objectives can also be measured with more concrete indicators (Level of noise, CO₂ emissions etc), that can also be used as assessment criteria of the success or not of a pricing scheme (CURACAO, 2009). This approach is more suitable for modelling purposes, where vague concepts simply cannot be applied and there have to be some quantifiable indicators. In the word quantifiable also lies the biggest problem of this approach. There are several objectives that cannot be (easily) quantified, for example acceptance or equity, which are also important factors for several stakeholders such as the government.

As can be seen, the first two approaches are more suitable for policy makers, whereas the latter is more appropriate for modelling purposes and/or evaluation of the program’s efficiency.

For the purposes of this thesis, the ‘targets’ of the stakeholders will be referred to as objectives, whereas the quantified indicators that stem from the users choices will be referred to as effects.

A specific scheme or measure may be more suitable for a specific objective, but a scheme may have more than one objective. In that case a hierarchical approach has to be made, namely to specify which objective is more important, and trade-offs between the objectives have to be identified and weighted.

List of objectives Identified

The CURACAO project has identified several objectives. The objectives that were identified can be seen in the table below (Table 6):

<table>
<thead>
<tr>
<th>Table 6, Objectives Identified</th>
</tr>
</thead>
<tbody>
<tr>
<td>Congestion Relief</td>
</tr>
<tr>
<td>Environmental Protection</td>
</tr>
<tr>
<td>Revenue Growth</td>
</tr>
<tr>
<td>Economic growth</td>
</tr>
<tr>
<td>Health</td>
</tr>
<tr>
<td>Liveability</td>
</tr>
<tr>
<td>Safety</td>
</tr>
<tr>
<td>Equity/Social Inclusion</td>
</tr>
<tr>
<td>Future Generations</td>
</tr>
</tbody>
</table>
The first 3 are the most important objectives that were identified in almost every city. The rest however are of emerging importance and thus consideration for the implementation authorities.

2.4. Stakeholders Involved in Pricing Schemes

Stakeholders (as identified by the EUROPRICE project2)

In every scheme the stakeholders that are first and foremost involved are:

- National government(s)
- European Union or similar organization
- Regional governments
- City councils
- State Agencies/Committees

These stakeholders are the ones with the power to implement or stop a project. Their power is high but their interest is influenced by social/economic factors.

The (main) stakeholders identified from the EUROPRICE project that can also be identified in most road pricing schemes examined are:

- Public Transport companies
- Motoring organisations
- Freight transport industry
- Cycling & pedestrian organisations
- Road safety agencies
- Vehicle manufacturing & servicing industry
- Manufacturers
- Trade unions
- Environmental organisations
- Civic societies (for example city history and architecture societies)
- Interest groups (for example elderly, impaired etc, either local or national)
- Chambers of Commerce (specific to town or city)
- Health organizations
- Financial Institutions
- Public Services (for example emergency services, public utilities etc)
- Retailers
- Leisure/tourist organizations

- Transport interchanges (organizations such as port or airport authorities and freight terminals)
- Employers
- Educational establishments

**Acceptance**
An important factor for the implementation of each pricing scheme is its acceptance from the users, as well as from all the other stakeholders involved. People tend to focus on their costs but forget or cannot compute the benefits they gain, therefore they are always beforehand reluctant to accept a measure that imposes an extra (out-of-the-pocket) cost. In addition to that, political reluctance, in fear of losing political support is always present in today’s democratic societies (CURACAO, 2009). These schemes cannot be implemented without prior consultancy of the stakeholders involved; therefore it becomes more obvious that acceptance will be a key factor. For a scheme to be accepted, it needs to be shown clearly that it will have a contribution to alleviating a problem that should also be clearly there (major traffic congestion, emissions problem etc.). Also stakeholders should be convinced that pricing is the suitable solution for alleviating this problem (Oehry, 2010).

Studies have shown that an important factor for a scheme to be acceptable is clear and predetermined use of revenues (see Ubbels & Verhoef, 2006 for information on the Dutch reality). However the problem of use of revenues will not be addressed in this thesis.

**2.5. Road pricing experience**

In the following table (Table 7), several pricing schemes around the world are examined, specifically on their objectives, the pricing measures used and the effects they had on the network and the environment. Information is taken from the CURACAO, 2009; Goh, 2002; Litman, 2005; Eliasson, Hultkrantz, Nerhagen, & Smidfelt-Rosqvist, 2009; Anas & Lindsey, 2011; and Santos & Fraser, 2006).
**Table 7, Overview of objectives, effects and pricing measures for several pricing schemes**

<table>
<thead>
<tr>
<th>City</th>
<th>Objectives</th>
<th>Pricing measures</th>
<th>Network and environment effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bergen</td>
<td>Revenue Growth</td>
<td>Variable toll (2 vehicle categories)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Congestion Relief</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bologna</td>
<td>Environmental Protection</td>
<td>Variable Permit</td>
<td>Decreased vehicular traffic</td>
</tr>
<tr>
<td>Bristol</td>
<td>Congestion Relief</td>
<td>Variable toll (morning)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Environmental Protection</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Liveability</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Economic Growth</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cambridge</td>
<td>Congestion Relief</td>
<td>Variable toll (morning peak, paid one-off)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Durham</td>
<td>Safety</td>
<td>Variable toll (paid on exit)</td>
<td>Decreased vehicular traffic</td>
</tr>
<tr>
<td></td>
<td>Equity/Social Inclusion</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Environmental Protection</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Edinburgh</td>
<td>Congestion Relief</td>
<td>Cordon pricing</td>
<td>Decreased traffic levels</td>
</tr>
<tr>
<td></td>
<td>Revenue Growth</td>
<td></td>
<td>Trip destination change</td>
</tr>
<tr>
<td></td>
<td>Equity/Social Inclusion</td>
<td></td>
<td>Increase in PT use</td>
</tr>
<tr>
<td></td>
<td>Environmental Protection</td>
<td></td>
<td></td>
</tr>
<tr>
<td>London</td>
<td>Congestion Relief</td>
<td>Variable toll (time of day-paid one-off)</td>
<td>Decreased car traffic</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Change of Destination</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Change of departure time</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Increase in PT use</td>
</tr>
<tr>
<td>Manchester</td>
<td>Congestion Relief</td>
<td>Variable cordon pricing</td>
<td></td>
</tr>
<tr>
<td>Milan</td>
<td>Environmental Protection</td>
<td>Variable Area license</td>
<td>Switch to more environmental-friendly vehicles</td>
</tr>
<tr>
<td></td>
<td>Liveability</td>
<td></td>
<td>Reduction in emissions</td>
</tr>
<tr>
<td></td>
<td>Economic Growth</td>
<td></td>
<td>Increase in PT use</td>
</tr>
<tr>
<td></td>
<td>Health</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nord-Jaeren</td>
<td>Revenue Growth</td>
<td>Flat toll (1 trip/hour)</td>
<td></td>
</tr>
<tr>
<td>Oslo</td>
<td>Revenue Growth</td>
<td>Variable toll (vehicle)</td>
<td></td>
</tr>
<tr>
<td>Rome</td>
<td>Congestion Relief</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Revenue Growth</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Environmental protection</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Singapore</td>
<td>Congestion Relief</td>
<td>Variable license, flat toll, dynamic cordon charging</td>
<td>Change in departure time</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Increased PT use</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Increased carpooling</td>
</tr>
</tbody>
</table>

*When a cell is left empty, it means that information was not available*
<table>
<thead>
<tr>
<th>City</th>
<th>Objectives</th>
<th>Pricing Measure</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stockholm</td>
<td>Congestion Relief, Environmental Protection, Liveability, Revenue Growth, Health</td>
<td>Variable cordon pricing</td>
<td>Decreased traffic within and across cordon, Decreased emissions, Increased PT use</td>
</tr>
<tr>
<td>The Hague</td>
<td>Congestion Relief</td>
<td>Reward for avoiding peak hours</td>
<td>Reduced peak-hour car trips, Increased PT use</td>
</tr>
<tr>
<td>Trondheim</td>
<td>Revenue Growth, Congestion Relief</td>
<td>Variable toll (time of day-1 charge per hour)</td>
<td></td>
</tr>
</tbody>
</table>

From Table 7 it becomes more evident that each scheme can have different objectives, different pricing measures and in the end different results on the network and environment conditions. Each scheme may also have more than one objective (for example Trondheim which had as a primary goal revenue generation and as a secondary goal traffic management). In addition to the objectives, the pricing measures may also have an effect on the outcomes. For example, in The Hague pricing scheme, they used a rewarding regime to make users avoid peak hour trips, whereas in London that had the same goal (at least this was the main one) they used flat tolls. Furthermore, the pricing schemes can have several differentiations that might make it difficult to categorize, for example Trondheim has a variable toll, depending on time of day, but also offers discount if the amount is prepaid. Several cities also embrace the notion of 1 charge per hour (Nord-Jaeren, Trondheim) which might be challenging for modelling purposes.

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4 A more detailed table with all the information on this table can be found in the Appendix (9.1)
Table 8 below summarizes Table 7, Overview of objectives, effects and pricing measures for several pricing schemes and gives a general overview of the pricing measures used and the objective they have an effect upon. Bolder x signs signify that those objectives were the main objectives for the pricing schemes the respective pricing measure was used and were more frequently considered.

Table 8, Pricing Measures and Associated Objectives (as observed from existing pricing schemes)

<table>
<thead>
<tr>
<th>Objective</th>
<th>Area pass</th>
<th>Cordon/zone charging</th>
<th>Toll</th>
<th>Distance-based charging</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F V D</td>
<td>F V D</td>
<td>F V D</td>
<td>F V D</td>
</tr>
<tr>
<td>Congestion Relief</td>
<td>x</td>
<td>x x</td>
<td>x x</td>
<td>-</td>
</tr>
<tr>
<td>Environmental Protection</td>
<td>x</td>
<td>x</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Revenue Growth</td>
<td>x</td>
<td>x x</td>
<td>-</td>
<td>Not yet examined in literature</td>
</tr>
<tr>
<td>Economic growth</td>
<td>x</td>
<td>-</td>
<td>x -</td>
<td></td>
</tr>
<tr>
<td>Health</td>
<td>x</td>
<td>-</td>
<td>x -</td>
<td></td>
</tr>
<tr>
<td>Liveability</td>
<td>x</td>
<td>x</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Safety</td>
<td>x</td>
<td>x -</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Equity/Social Inclusion</td>
<td>x</td>
<td>x -</td>
<td>x -</td>
<td></td>
</tr>
<tr>
<td>Future Generations</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

*F=Flat, V=Variable, D=Dynamic
2.6. Conclusions

Road pricing is regarded as an efficient tool for internalizing external costs, costs that travellers might not be aware that they impose or they tend not to consider. Each road pricing scheme consists of 3 main components. First, the pricing type of the measure, which can be one of area pass, cordon/zone charging, point based charge (e.g. tolls) and distance based charging. Secondly, the price level of each measure and finally the differentiation of the price, according to the vehicle type, user group, location of application of the pricing scheme and time of application. If the price remains the same is called flat, if there are some differentiations that are pre-determined it’s called variable and if the measure is dependent on the conditions of a specific instance (for example the actual levels of congestion) is called dynamic. From the international experience of road pricing it can be concluded that the main objectives observed are congestion relief, environmental protection and revenue growth. Other objectives observed were economic growth, health, liveability, safety, equity and future generations. The main pricing measures used are variable area pass, variable and dynamic cordon charging and flat or variable tolls. The main stakeholders involved, that can control the pricing measures are the government (regional or national, city councils and state agencies. Other stakeholders involved, that cannot control a pricing measure but can be of importance for the success of the scheme include Public Transport and Public Services, traveller organizations (motorists, cycling and pedestrian), environmental organizations and stakeholders of economic interest (financial institutions, retailers, manufacturers etc). An important factor of success for most of the pricing schemes that was identified is the acceptance of the travellers.
3. General Framework

This chapter explores the mathematical theory behind road pricing decision-making process, which is represented by a bi-level formulation, as well as it gives a brief overview of the game theory concepts that describe the bi-level process and the interaction between the users in the lower level. In the upper level lie the decision making authorities, which can either impose and determine a specific pricing measure or they can just influence the process in order to ensure that specific objectives are taken into account. The outcomes of this level are the specifications of the pricing measures and price levels. On the lower level lie the users. The users, taking into account the pricing measures and the prices adjust their transport choices. The outcomes of this level are several measurable effects that can be used in order for the decision making authorities to assess the success of their pricing decisions by checking the degree of fulfilment of their objectives. The upper level process is examined for the case of multiple stakeholders, which is the main objective of this thesis, and the game theory concepts behind their interaction are presented (cooperative, non-cooperative case and the notion of veto player). For the lower level, an insight is given on the user choices and how a pricing measure can affect these choices. The effects that can be measured as an outcome from this process are presented. Finally, the upper level process is reformulated in order to incorporate the acceptance of the users in the modelling process with the use of game theory.

3.1. Mathematical background of road pricing

The process that takes place is the following: A decision-making authority (road owner, ministry etc.) decides to pose a fee for the use of a road. Logically, it wants to know whether the fee that it imposes serves its agenda and eventually determine the “right” price. In order to determine this best price, it has to know how the users of the road will react to his decisions. For example, if it wants to achieve profit maximization, the best strategy may not be to impose a bigger fee, because this will lead users to follow other routes to avoid the fee. Mathematically, this process can be best described by the following bi-level formulation (LeBlanc & Boyce, 1986):

Upper Level:
\[ \min_y F(x, y) \]

Lower level:
\[ \min_x f(x, y) \]

s.t. \[ g(x, y) \geq b \]

The upper level describes the process taking for the decision-making authority: The authority has set a specific goal-the objective function \( F(x, y) \), which he/she tries to optimize. In the
road pricing example, the upper level represents the optimization of the objective(s) of the authority setting the price (which can be one or more from those stated in Table 6), which is constrained by the users reactions to this price. Some of the variables depend on the lower level program, namely the optimization of function \( f(x, y) \), which represents the users’ objectives. This function can be subject to constrains, represented by the function \( g(x, y) \). The lower level represents the users’ goal to minimize their travel costs when they choose their route. This decision can be constrained by their time and money budget, departure time and several other factors.

As can be understood from the previous paragraph, the road pricing setting represents a hierarchical relationship between 2 decision levels, namely the decision-making authority setting the price in the upper level and the road users in the lower level. With the use of game theory, this interaction can be represented by a Stackelberg game, a game where the leader makes a move (in this example a stakeholder that imposes the price) and the follower reacts accordingly (road users that choose a route) (Fisk, 1984; Colson, Marcotte & Savard, 2007). In this kind of game it is assumed that the leader can predict how the follower will react and can design his strategy accordingly. In the lower level, users choose their route by pursuing the maximization of their personal welfare. An equilibrium of flows is reached when no user can increase their personal welfare by unilaterally change their route (according to Wardrop’s principles). This kind of interaction, between the users in the lower level, can be best modelled by a Nash non-cooperative game (Fisk, 1984).
3.2. Processes in the upper and lower level

The general process that takes place in order to determine the price of a pricing measure can be observed in Figure 3.

In the next sections, the processes that take place in the upper and lower level in the case of a multi-stakeholder environment, as well as the outcomes (effects) of this process will be examined.

3.2.1. Upper Level:
As mentioned before, on the upper level lie the decision authorities. Since these authorities are usually more than one, there is interaction also between them, not only with the users on the lower level. These authorities can either compete, giving rise to use of non-cooperative game theory, or cooperate and give rise to use of cooperative game theory concepts.

Non-Cooperative
In the non-cooperative case each stakeholder decides individually his strategy, without knowing the moves of the other stakeholders, only how they affect their objectives. Their goal is to
maximize their individual profit. The stakeholders are involved in a Nash game. Equilibrium is reached when no stakeholder can improve their own objective by changing only their own strategy. It can be said that each stakeholder is solving his own bi-level program simultaneously with the other stakeholders’ bi-level programs. Mathematically, the traditional Mathematical Program with Equilibrium Constraints (MPEC) that is used to solve traditional bi-level programs is transformed into an Equilibrium Program with Equilibrium Constraints (EPEC) (Ohazulike, Bliemer, Still, & Berkum van, 2012):

![Diagram](image)

**Figure 4, Upper level for the non-cooperative case**

The bi-level process is shown below (Figure 5). It should be noted that each pricing measure, based on its characteristics goes into the route or the link cost equation.
Figure 5, Diagram of the bi-level process for the non-cooperative case
**Cooperative**

In the cooperative case, it is assumed that the stakeholders can benefit by cooperating and binding agreements are possible, meaning they can discuss beforehand and decide on a joint strategy before applying it. The goal in this case is to maximize their combined gains. It is assumed of course that no stakeholder goes into coalition if their personal gain is not greater than their profit in the non-cooperative case. Mathematically, when a coalition is formed, the bi-level program can be seen as a traditional one leader-multi follower (Stackelberg game) bi-level program, but this time having the coalition as the leader (Ohazulike, Bliemer, Still, & Berkum van, 2012). The problem is if and how they can reach an agreement.

Cooperative games can be divided into two main categories, Transferable Utility Games (TU) and Non-Transferable Utility Games (NTU). In the first case, side payments can occur from one stakeholder to another in order to induce the formation of coalition, whereas in the second case side payments are not allowed. This research will focus on the TU games, since road pricing games are cases where side payments can occur.

The ideas behind cooperative games are as follows:

- Even though all the stakeholders work together, they are still selfish.
- The coalitions and the distribution of profits should be such that no stakeholder(s) has an incentive to leave the coalition.
- In some cases fairness of the distribution of profits should be ensured. This means that every stakeholder should receive an amount of profit proportional to their contribution.

The aforementioned ideas can be mathematically described as follows:

A TU game is a pair $G = (N, v)$ where $N = \{1, \ldots, n\}$ is the set of players (stakeholders) and $v : 2^N \rightarrow R$ is the characteristic function which assigns a ‘worth’. $C$ is a subset of players (coalition) and $v(C)$ is the amount of “worth” that the coalition $C$ can earn by working together. A coalition is any subset of $N$, with $N$ itself called the **Grand coalition**.

An **outcome** of a TU game $G = (N, v)$ is a pair $(CS, x)$, where $CS = (C_1, \ldots, C_k)$ is a coalition structure, meaning partition of $N$ into coalitions and $x = (x_1, \ldots, x_n)$ is a payoff vector, which distributes the value (worth) of each coalition in $CS$. $x_i \geq 0$ for all $i \in N$.

An outcome $(CS, x)$ is called an **imputation** if it satisfies **individual rationality**: $x_i \geq v(\{i\})$, meaning the payoff to each stakeholder should be at least equal to the value they could achieve by themselves, if not cooperating.

An efficient allocation assigns all value generated to the players of a coalition.
Solution Concepts

There exist several solution concepts in literature. The main problem is the allocation of profits so every stakeholder has an incentive to form the coalition and not deviate from it. The concepts that are more widely used are explained below:

The Core:

The Core of a game is the set of all stable outcomes, meaning all outcomes that no coalition or stakeholder wants to deviate from. \( \text{Core}(G) = \left\{ (CS, x) \mid \sum_{i \in C} x_i \geq v(C), C \subseteq N \right\} \). This means that each coalition earns at least as it can make on its own. The core consists of allocations that are both individually rational and efficient. The core can be regarded as an incentive for stakeholders to cooperate. If the core exists however there may exist several allocations of the combined gains.

The Shapley Value:

The allocations in the core might not be fair. A fair allocation should reward each player according to his contribution to the gains (winnings) for the coalition. The Shapley value assigns to each player the average marginal contribution to the coalition. Shapley value can be explained in plain words as follows: Given a game with a fixed amount of players, let the players join the coalition one at a time, in a predetermined order. The player’s contribution to the coalition is his net addition to the profit when he joins the players that have already joined. The Shapley value of a player is his average gain (winnings) contribution over all possible orderings of the players. This marginal contribution is denoted by \( \varphi_i \).

The Shapley value has the following properties:

- **Efficiency**: \( \varphi_1 + \ldots + \varphi_n = v(N) \). The sum of all the marginal contributions of each stakeholder should sum up to the total extra value that stems from the coalition.
- **Dummy**: if \( i \) is a dummy, \( \varphi_i = 0 \). If \( i \) does not bring extra value to the coalition, his marginal contribution is 0.
- **Symmetry**: if \( i \) and \( j \) are symmetric, then \( \varphi_i = \varphi_j \).
- **Additivity**: \( \varphi_i(G_1 + G_2) = \varphi_i(G_1) + \varphi_i(G_2) \). This means that the sum of payoffs of 2 separate games should be the same if these 2 games were to be remodelled into 1 game.

In order to incorporate the users’ acceptance in the games taking place in the decision process, the approach adopted for this research is with the notion of veto player. In game theory, a veto
player is any player that if he/she is not part of a coalition, then this coalition is losing. In mathematical terms, \( i \) is a veto player if \( v(N \setminus \{i\}) = 0 \).

The process that takes place in the upper level, in a cooperative case, is shown below in Figure 6.

![Figure 6, Upper level for the cooperative case](image-url)
In the following diagram (Figure 7), the general bi-level process is shown for the cooperative case:

Figure 7, Bi-level process for the cooperative case
3.2.2. Lower Level:
The lower level consists of the travellers’ choices regarding the imposed pricing measures. Travellers choose their route with a goal to minimize their (perceived) travel cost. This cost may consist of several factors, mainly including travel time and pricing measure cost (other components may include comfort, vehicle ownership). From a modelling perspective, the process that takes place is as portrayed in Figure 8:

The outcome of the upper level is the pricing schemes applied, including their characteristics (flat/variable/dynamic, tax/pass/license/toll etc) and their price. These 2 factors mainly affect the users’ route costs. Different measures also have different effects on other users’ choices, namely Departure time, Mode and Origin and Destination choices (for example a variable toll differentiated by time of day affects some users by making them depart earlier or later to avoid paying the fee, whereas a daily pass does not affect their departure time, but can affect their mode choice for instance).
User responses to road pricing

In this section it will be assessed how different pricing measures can affect the choices of the users in the lower level. Since the travellers’ choices are mainly affected from the generalized cost of the route, on a specific time of day and place, it is examined first how each pricing measure, based on its characteristics can be included in the cost function.

Cost Function

A road pricing measure adds an extra cost component to the users’ cost, except for the time cost (the time it takes to make a trip) and other cost components that the users may take into account, such as frequency of a bus line, comfort. Since users make their choices based on their experienced cost, an extra cost component can affect their choices. Based on the characteristics of each pricing measure (time-dependant, distance based, paid per crossing etc) they can affect different choices. The road pricing measures can be modelled as an extra term of the user cost equation. According to the type of pricing measure, these terms can be in the form explained below:

Pass/License: The general form of this component is $c^p$, where $c^p$ the price of the pass or license. If multiple and/or different passes are needed for different areas, then the cost is $n \times c^p$, where $n$ denotes the number of passes needed, for every area and for every different pass. The pass is usually a measure that is applied on route level.

Distance-based: The general form of this measure is $c_{km}^{uc}$, which represents the price of the km charge for a specific user group. The measure has to be multiplied by the distance travelled. The km charging can be differentiated based on different characteristics, time of day. For dynamic pricing, the km charging has to be updated every time interval and should be multiplied with the distance travelled during that time interval and include also the possible differentiations.

Tolls: The general form is $c_{toll}^{uc}$, which represents the price of a toll for a specific user class. However how it is incorporated in the cost function has several differentiations. If there are several tolled links on the network, then simply the cost from tolls is the sum of those toll prices, for every tolled link travelled, according to the differentiations that exist depending on the specific characteristics of each pricing scheme (for example based on vehicle type, time of day, income, engine type) and if there exist differentiations based on specific conditions (dynamic pricing). If the toll is imposed on route level, for example if a user’s route includes a specific toll road that charges users once upon entry or exit, then the cost function needs different treatment and the costs have to be calculated on route level. However, there exist schemes that may have special characteristics, such as the toll is to be paid once per hour. In these situations the cost function should be treated based on the specific characteristics of that specific scheme.

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5 Following the analysis of (Joksimovic, Van Amelsfort, & Bliemer, 2002)
Other pricing measures can be modelled based on the previous forms. For example, a fuel tax can be considered as a km charge, a vehicle ownership tax can be seen as a form of pass etc.

**Route Choice:**

The most basic response to a road pricing measure is to change one’s route in order to avoid it (Joksimovic, Van Amelsfort, & Bliemer, 2002). Users may choose a different route to avoid a pricing measure. However, this depends on their Value of Time (VOT), income and actual price of the pricing measure. If for example the pricing measure is adequate to force enough people of lower VOT out of a specific route and consequently lead to lower travel time on that specific route, other users might opt to change back again to this route.

It is apparent that different modelling techniques can tackle different measures better. For example, a simple pricing scheme with flat or variable tolls can be tackled with a simple static user equilibrium assignment, either Stochastic or Deterministic. However a more elaborate scheme, for example a dynamic congestion scheme, needs more elaborate modelling techniques such as the Dynamic Traffic Assignment that can allow for incorporation of congestion and queuing effects (Vovsha, Davidson, & Donnelly, 2005).

**Departure Time choice:**

Costs depend on the time a user starts his journey. If a trip is to be made on-peak, the amount of congestion that is usually higher than off-peak will lead to higher time cost. In addition to that, there may be an extra fee charged (for example a toll imposed only on-peak). For this reason users might change their departure time. This way they are avoiding the extra time costs imposed on them and possible road pricing fees imposed on-peak. However, in this case they have to take into account that an earlier or later departure may help them avoid the congestion that may be present on specific areas on specific times but this will lead to earlier or later departure, which might not be preferable or even not possible (for example the user class of commuters that cannot reach their work very late). For these reasons it is important to provide information through the modelling process about departure time choice. In order to examine the effects of pricing to departure time choice, an extra component can be incorporated into the user cost function that will consist of a penalty for early or late departure, in addition to the cost of the pricing measure.
**Origin and Destination Choice:**
Some users might be able to change their destination, mostly for non-work related trips, in order to avoid a pricing measure (as in the London example). This is easier to be done for recreational and leisure trips rather than commuter trips. In order for travellers to change their origin, it means that they have to move. This is usually a more long-term effect because it needs extra motivation to convince people to move because of a pricing measure; usually this will be the result of an already under consideration option for moving (Joksimovic, Van Amelsfort, & Bliemer, 2002).

**Mode choice:**
It is usual phenomenon with the introduction of charging schemes that travellers shift from car to other modes of transport, which can include bike, Public Transport or walking. Users might change their mode in order to avoid this extra cost component, especially if the time gains from other users shifting their choices are not of the same magnitude. The determinants of this choice will again be time and out-of-the-pocket costs, as well as comfort, egress time etc. In addition to this, there is evidence of increased ridership (carpooling) (Singapore example). Nowadays, telecommuting should also be considered as a choice (work from home).

**Cancel trip:**
Depending on the fee, people may cancel unnecessary trips (for leisure for example) or may combine them with other trips (the Stockholm congestion-charging trial).

In the table below (Table 9) the influence that the different pricing measures can have on the lower level of the bi-level program (from a modelling point of view) are summarized. This table is based on the road pricing schemes examined before and on the paper of May & Milne, 2000.

<table>
<thead>
<tr>
<th>Table 9, Association between pricing measures and user choices</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>User Choices</strong></td>
</tr>
<tr>
<td>------------------</td>
</tr>
<tr>
<td>Route choice</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Departure time choice</td>
</tr>
<tr>
<td>Destination choice</td>
</tr>
<tr>
<td>Cancel trip</td>
</tr>
<tr>
<td>Mode choice</td>
</tr>
</tbody>
</table>

*F=Flat, V=Variable, D=Dynamic*
3.2.3. Effects

The effects are measurable indicators that help assess the fulfilment or not of the policy objectives set by the decision making authorities. These can include number of accidents, emissions, noise, road pavement damage, total travel time, congestion, user surplus and even revenues generated. These effects can be expressed in their respective measurement for example time cost in minutes) or they can be transformed into monetary units, so they can be easily compared. The equation form depends on the purpose (internal of the model or for presentation to external authorities).

*Equations*

**Accident:**

\[
S = \sum v_i \left( r_i d_i + TT_i \right) \quad \text{(number of injury crashes) or}
\]

\[
S = a \sum v_i \left( r_i d_i + TT_i \right) \quad \text{(in monetary units)}
\]

**Emission:**

\[
E = \sum v_i \kappa d_i \quad \text{(in CO}_2\text{grams) or}
\]

\[
E = \varepsilon \sum v_i \kappa d_i \quad \text{(in monetary units)}
\]

**Noise:**

\[
N = \sum \left[ A + B \log \left( \frac{u_i}{u_{ref}} \right) + 10 \log \left( \frac{f_i}{f_{ref}} \right) \right] h_i \quad \text{(in dbA) or}
\]

\[
N = \sum \gamma \left[ A + B \log \left( \frac{u_i}{u_{ref}} \right) + 10 \log \left( \frac{f_i}{f_{ref}} \right) \right] h_i \quad \text{(in monetary units)}
\]

**Road Pavement Damage:**

\[
I = \sum v_i \tau \left( \frac{H}{f_i} \right) d_i \quad \text{(in monetary units)}
\]

**Time Cost:**

\[
T = \sum TT_i v_i \quad \text{(in time units) or}
\]

\[
T = VOT \sum TT_i v_i \quad \text{(in monetary units)}
\]

**Revenues Generated:**

\[
R = \sum c_i^r f_i \theta_i + \sum c_i^toll f_i \theta_i + \sum c_i^{lm} v_i d_i \theta_i - \sum O \quad \text{(in monetary units)}
\]

**User Surplus:**

\[
U = \sum \text{benefits} - \sum \text{costs}
\]

User surplus is defined as the benefit which a user enjoys after the costs he/she has to undergo for this benefit (Department for Transport, 2004). Depending on each specific pricing scheme, the benefits and the costs might be different, that is why the formulation above is a rather

---

6 These equations were adopted from Ohazulike et al., 2012 and own experience
general one. For this research, users surplus will be calculated as the monetized net balance between the time benefits and the out-of-pocket costs (see also chapter 4.3). The equation for this case will be the following:

\[ U = (TTT_i - TTT_0) - \left( \sum c_{\text{toll}} f_i r_i + \sum c_{\text{km}} v_i d_i \theta_i \right) \]

Annotations:

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f_r )</td>
<td>Route Flow on route ( r )</td>
</tr>
<tr>
<td>( v_i )</td>
<td>Total flow on link ( l )</td>
</tr>
<tr>
<td>( r_i )</td>
<td>Risk factor for link ( l ), measured in number of injury crashes/veh-km</td>
</tr>
<tr>
<td>( \kappa )</td>
<td>Emission factor (per km driven)</td>
</tr>
<tr>
<td>( TT_i )</td>
<td>Travel Time on link ( l )</td>
</tr>
<tr>
<td>( \theta_r )</td>
<td>1 if there is a road pricing measure imposed on route ( r ) (toll or pass), 0 otherwise</td>
</tr>
<tr>
<td>( \theta_i )</td>
<td>1 if there is a distance-based road pricing measure imposed on link ( l ), 0 otherwise</td>
</tr>
<tr>
<td>( \epsilon )</td>
<td>Price of a gram of CO(_2)</td>
</tr>
<tr>
<td>( \gamma )</td>
<td>Price per dbA (price depends on the level of dbA)</td>
</tr>
</tbody>
</table>
3.3. Proposed reformulation

In the proposed reformulation as can also be seen in Figure 9, Proposed reformulation of the upper level for the cooperative case, a stakeholder representing the users will also participate in the upper level decision making process. This stakeholder will be modelled as a veto player. The process is as follows: The stakeholders that control the road pricing measures will proceed in a cooperative game play. This veto player will then accept to be part in any coalition that fulfils his/her objective(s). Any coalition that does not have the veto player as a member will not be enforced. In the non-cooperative case, this veto process will be incorporated as an extra constraint. If the solution vector does not satisfy the objective(s) of the veto player then it will not be accepted.
3.4. Conclusions

The road pricing can be represented as a bi-level program, having in the upper level the decision-making authority and in the lower level the users. The decision-making authority tries to optimize his/her objective(s), constrained by the reaction of the users in the lower level, who try to minimize their travel cost. The interaction between the upper and the lower level can be represented by a Stackelberg game, whereas the interaction between the users inside the lower level can be represented by a Nash non-cooperative game. If more than one decision-making authorities (stakeholders) exist in the upper level the bi-level program needs to be reformulated. In the non-cooperative case, the authorities decide individually their strategy with a goal to maximize their own objective. It can be said that each stakeholder is solving his own bi-level program simultaneously with the other stakeholders’ bi-level programs. The stakeholders between them are also in a Nash non-cooperative game. In the cooperative case the stakeholders decide on a joint strategy before applying it, with a goal to maximize a common objective. There exist two kinds of cooperative games, the Non-Transferable Utility and the Transferable Utility games. Since in road pricing cases it is possible to have compensations and transfer of payments, this research focused on the TU games. The main solution concepts that exist for cooperative games are the core and the Shapley value. The core represents all the allocations of the gains achieved through the formation of a coalition that yield bigger gains for the stakeholders than in the non-cooperative case. If the core exists the stakeholders can form a coalition that they do not want to deviate from. There might exist more than one allocation though in the core. The Shapley value is an allocation method of the coalitional gain that assigns to each stakeholder its average marginal contribution to the coalition. For this research, user acceptance will be modelled in a game theoretic approach using the notion of a veto player. A veto player is any player that if he/she is not part of a coalition, then this coalition is losing, in other words it cannot be formed. The effects are measurable indicators that help assess the fulfilment or not of the policy objectives set by the decision making authorities. These effects can be expressed in their respective measurement (for example time cost in minutes) or they can be transformed into monetary units, so they can be easily compared. Effects that can be measured from this bi-level process include accidents, emissions, noise, road pavement damage, time cost, user surplus and revenues generated.
4. Case study

The aim of the research is twofold: on one hand, the main goal of this research was to examine whether cooperation between the stakeholders responsible for setting the price of the pricing measures can yield different results from the case in which the stakeholders choose individually their price (non-cooperative case). The acceptance of users for these pricing schemes is also examined and in the end if and how the aforementioned framework can be used from policy-makers. On the other hand the aim of this research was to examine the effects of different pricing measures on different objectives as well as to examine the effect on the users’ choices when they travel. The focus of this research is to examine “the bigger picture”, namely not to focus on the actual results but to identify whether the pricing measures can affect the choices of the users and in which direction and whether a game theoretic approach can produce interesting results regarding cooperation or competition between the stakeholders, as well as if these results are acceptable from the users.

In order to answer these questions, a case study was set up. It should be noted that the case study applies to a real area (extended Randstad) with realistic data; however, because of the necessary assumptions behind the developed model due to the limited time available for the study, the results are not for use as actual values but rather as an indication.

The case study area was chosen and coded with OmniTrans software. Data was then collected from the Statistical Bureau of Netherlands regarding commuter travellers. A model was developed again in OmniTrans which models two different users’ choices, namely route choice and time of departure choice. Users are considered to have fixed Origins and Destination and the demand is also fixed. They are assumed to first choose their time of departure based on their route travel time and the costs of their route, which are different on-peak and off-peak. On-peak, in addition to the travel time they also have to take into consideration two pricing measures, kilometre charge on the highways and a cordon pricing for passing through Amsterdam. Off-peak their route cost consists only of their travel time and an extra penalty their assumed to face if they change their departure time, either before or after their preferred departure time which is during the peak. After they choose when to travel, they are assigned to the network and they choose their route. Eventually the flow pattern will be under user equilibrium, meaning no user can change his or her route without increasing their travel cost.

Finally, after getting the flow patterns for several pricing scenarios, the Total Travel Times for the whole network and the emissions for the city centre of Amsterdam are calculated. Based on these results it is examined which scenario will yield better results; if the stakeholders cooperate or if they do not cooperate. These schemes will be checked also if they are acceptable from the users through a veto process where their stakeholder, ANWB, is included.
4.1. Case study Area

The area of consideration is an extended Randstad area, as shown below:

![Figure 10, Case study Geographical area: Extended Randstad area](image)

The Randstad is an urban configuration in the western part of the Netherlands. It includes the biggest cities of the Netherlands, such as Amsterdam, Rotterdam, The Hague and Utrecht. In the Randstad lie the majority of jobs of the Netherlands, as well as important economic centres such as the port of Rotterdam and Schiphol airport. The area chosen for this research is an extended Randstad area, following the analysis of the Polynet project (Institute of Community Studies/The Young Foundation & Polynet Partners, 2005). The case study area extends from ’s-Hertogenbosch and Dordrecht in the South, to the Alkmaar and Hoorn in the north, and from Den Haag in the west to Arnhem and Nijmegen in the east. In this area lie also some of the busiest highways of the Netherlands.

The case study area was then represented in OmniTrans as follows:
Figure 11, Network of the case study in OmniTrans
The study area consists of 27 centroids that constitute origins and destinations for commuter travelling. The centroids included are shown in the table below (Table 10):

Table 10, Cities modelled and their corresponding number in Omnitrans

<table>
<thead>
<tr>
<th>Centroid number</th>
<th>Centroid name</th>
<th>Centroid number</th>
<th>Centroid name</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Amsterdam</td>
<td>15</td>
<td>Dordrecht</td>
</tr>
<tr>
<td>2</td>
<td>Rotterdam</td>
<td>16</td>
<td>Gouda</td>
</tr>
<tr>
<td>3</td>
<td>Alkmaar</td>
<td>17</td>
<td>Delft</td>
</tr>
<tr>
<td>4</td>
<td>Leiden</td>
<td>18</td>
<td>Zoetermeer</td>
</tr>
<tr>
<td>5</td>
<td>Den Haag</td>
<td>19</td>
<td>Purmerend</td>
</tr>
<tr>
<td>6</td>
<td>Breda</td>
<td>20</td>
<td>Haarlem</td>
</tr>
<tr>
<td>7</td>
<td>Arnhem</td>
<td>21</td>
<td>Alphen aan de Rijn</td>
</tr>
<tr>
<td>8</td>
<td>Hoorn</td>
<td>22</td>
<td>Amstelveen</td>
</tr>
<tr>
<td>9</td>
<td>Zaanstad</td>
<td>23</td>
<td>Almere</td>
</tr>
<tr>
<td>10</td>
<td>Amersfoort</td>
<td>24</td>
<td>Hilversum</td>
</tr>
<tr>
<td>11</td>
<td>Utrecht</td>
<td>25</td>
<td>Gorinchem</td>
</tr>
<tr>
<td>12</td>
<td>Veenendaal</td>
<td>26</td>
<td>Schiphol</td>
</tr>
<tr>
<td>13</td>
<td>Nijmegen</td>
<td>27</td>
<td>Ijmond</td>
</tr>
<tr>
<td>14</td>
<td>s-Hertogenbosch</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

For this network 6 different road types were modelled. The characteristics of the links of the network (speed and capacity) are shown in Table 11. These characteristics were taken from the report “Documentatie van GM 2011-Programma QBLOK” (2011).

Table 11, Road types modelled and their characteristics

<table>
<thead>
<tr>
<th>Type</th>
<th>Speed (km/hour)</th>
<th>Capacity (vehicles/hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>50</td>
<td>2400</td>
</tr>
<tr>
<td>ME</td>
<td>120</td>
<td>6975</td>
</tr>
<tr>
<td>D</td>
<td>80</td>
<td>3000</td>
</tr>
<tr>
<td>OE</td>
<td>50</td>
<td>1200</td>
</tr>
<tr>
<td>DE</td>
<td>50</td>
<td>1200</td>
</tr>
<tr>
<td>M</td>
<td>120</td>
<td>6975</td>
</tr>
</tbody>
</table>
4.2. Choices for the lower level

For this report a static model was employed, which was applied for two distinct time periods, namely on-peak and off-peak. It was assumed that for the specific case a static model will yield satisfactory results in order to test the theory of cooperation or non-cooperation between the stakeholders and give a general observation on the effects of the pricing measures on the users’ choices. A Deterministic User Equilibrium (DUE) approach was followed for the traffic assignment. This approach takes into account the congestion effects; hence it yields more accurate results than other simple assignment methods such as all-or-nothing assignment or the simple stochastic assignment that can be used in OmniTrans. Stochastic User equilibrium (SUE), which takes into consideration also a difference in the perception of costs from the users, was deemed unnecessarily complex and demanding for the scope of this research.

Users and Mode

For the case study one user class is examined, namely commuters and one mode of travel can be used, the car. The Origin-Destination (Origin-Destination) data that were used were collected from the Statistical Bureau of the Netherlands (Centraal Bureau voor de Statistiek, 2013). These data actually represent the number of people traveling from their place of residence to the place of work. It was assumed that all these people travel every day to go to work and that they all go during the morning. Of course not all these people use their car to go to work and of course there might be more than one commuter in one car. For these reasons, the available data had to be scaled so as to represent as close as possible the Dutch road traffic reality.

Users are assumed to choose their route based on its generalized cost. These generalized costs for travelling are assumed only to include the cost of travel time, the cost of the pricing measure and the penalty for departing earlier or later. The cost equations are shown below:

Travelling On-Peak: \[ C_{OP} = VOT \times TT_r + c_{cor} + c_{km} \times d \]

Travelling Off-peak: \[ C_{OFF} = VOT \times TT_r + P_{dep} \]

Where \( C_{OP} \) and \( C_{OFF} \) are the cost functions for on-peak and off-peak respectively, \( VOT \) is the Value of Time that the users assign to their travel time, \( c_{cor} \) is the price of the cordon pricing toll, paid per entrance in the city of Amsterdam, \( c_{km} \) is the kilometre charge, \( d \) is the length of the (part of) the route that the kilometre charge is applied to and \( P_{dep} \) is the penalty that the users face for departing earlier or later than their proffered time.
Travel times on specific routes were taken from the website of Tripcast (Tripcast, 2013) to assess the resulting travel times of the model. This site gives times for travelling by car taking into account the effect of congestion.

The most important cost for a traveller is the travel time between origin and destination. A traveller always tries to minimize his personal cost, and one of the major perceived costs during travel is the time of the trip. Therefore, users will change their route if there is a route with lower travel time. For this research, it is assumed that travel time only consists of the in-vehicle travel time.

Travel time is greatly influenced by congestion. In order to capture that, the well-known BPR function is used.

\[
TT_i = t_0 \left[ 1 + a \left( \frac{v_i}{C_{0,i}} \right)^b \right],
\]

Where \(TT_i\) is the travel time on link \(l\), \(t_0\) is the free-flow travel time on link \(l\), \(v_i\) is the actual flow on the link \(l\) and \(C_{0,i}\) the capacity of the link \(l\). For highways (M and ME type of roads) the values of \(a = 0.5\) and \(b = 6\) were used, whereas for all the other roads values of \(a = 2\) and \(b = 4\) were used. This distinction was made because it is assumed that the effect of congestion on smaller roads is greater than on the highways (values of \(a\)).

Travel costs also include the costs for other attributes of the travel, namely fuel cost, parking costs, toll charges. In this research however only toll charges are taken into account. Users try to minimize these additional costs. However, routes with no tolls may have higher travel times because of higher congestion and/or lower speeds. Therefore users always try to optimize the time and cost combination, namely their generalized cost. In this research, travel costs are time dependent. If travellers choose to travel off-peak, they do not have to pay extra costs (tolls). However, if they choose to travel on-peak they have to face the kilometre charge on the highways and the cordon toll when entering Amsterdam if their route ends or just passes through Amsterdam.

One extra cost, which users take into account but they do not actually pay, is the extra cost they face if they leave earlier or later. This cost is taken into account when users have to choose when to travel. If they decide to travel on-peak they do not face this penalty but only the extra road pricing charges, however if they decide to travel off-peak they will not pay extra charges but they will have to take into account the penalty for leaving outside their preferred time. For on-peak travelling the departure time is assumed to be 8.00 a.m, whereas the off-peak is assumed to be 1 hour earlier or later. The price for this penalty is taken from the PhD research of Van Amelsfort (2009). According to his research, he calculated the value of departing earlier from the preferred time equal to 7 €/h, whereas the value for departing later 74 €/h. This difference is to be expected because commuters prefer to leave earlier and subsequently arrive
earlier than depart and arrive later at work. For the present research a unified penalty was taken into account, which holds for both departing earlier or later and is the average price of the aforementioned prices, namely 40 €/h. The penalty is calculated for 1 hour earlier or later departure, so the total of the penalty is €40.

Finally, $VOT$ was taken equal to 19 €/h (Van Amelsfort, 2009).

**Departure time Route Choice model**

The steps followed in the lower level in order to calculate the flow patterns in the network are as follows:

Based on the free-flow times on the network the initial travel costs are calculated between the Origin-Destination matrices. The costs for the Off-peak are increased by the penalty of departing off-peak, which is equal to €40. Based on these initial costs a simple Multinomial (MNL) logit model is applied to calculate the probabilities of choosing whether to travel on peak or off peak. Then the initial Origin-Destination is multiplied with these probabilities so as to produce the on-peak and off-peak Origin-Destination matrices.

The above process is shown below:

$$P(OP) = \frac{e^{pl_{op}}}{e^{pl_{op}} + e^{pl_{off}}}$$

$$P(OFP) = 1 - P(OP)$$

$$OD_{OP} = P(OP) * OD$$

$$OD_{OFF} = P(OFP) * OD$$

$P(OP)$ and $P(OFP)$ are the probability for a traveller to choose to travel on-peak and off-peak respectively. $U_{OP}$ and $U_{OFF}$ the utility of travelling on-peak and off-peak respectively, $OD$ is the initial Origin-Destination matrix and $OD_{OP}$ and $OD_{OFF}$ are the Origin-Destination matrices that are produced after the users have chosen whether they want to travel on-peak or off-peak respectively. It should be noted that this process is done for every Origin-Destination pair.

These matrices are then separately assigned on the network, on peak with both the pricing measures and off-peak with no measure. The assignment followed is a deterministic user equilibrium assignment, meaning each user is completely rational and has complete knowledge of the network and flows. The flows are in equilibrium when no user can improve their cost by unilaterally shifting from one route to another. This concept is based on Wardrop’s first
Principle which states that “The journey times for all routes actually used are equal or less than those which would be experienced by a single vehicle on any unused route”.

From the assignment process the flow pattern over the network is produced. This flow pattern is used to calculate the new costs between the Origin-Destinations for every route, which now include the new travel times. Based on these new costs the process starts again.

The model has to perform the loop shown above until it converges. One outer loop takes approximately 3-4 minutes to perform (depending on how many iterations are needed in the assignment process, set to 35 for the on peak assignment and 50 for the off-peak). 40 outer loops were performed for each scenario in order for the flows on-peak and off-peak to converge, meaning each scenario needed 2 to 2.5 hours. Overall there were 25 scenarios modelled, so in order to produce results for all the scenarios more than two days of calculations were needed. This big amount of calculation times was needed because of the difficult nature of calculations for kilometre charge.

**Convergence**

For achieving equilibrium during the inner loops of the Deterministic User Equilibrium assignment, OmniTrans uses the Method of Successive Averages, which has been found to
effectively produce convergence. For the outer loop, because of the time demand for producing results, the convergence of the travel times between some of the Origin-Destination pairs was not perfect. This is also due to the fact that MSA was not used, because of the further complexity it would bring to the model code. However it was calculated that the difference of Total Travel Time between the last iterations was around 2%, which was considered accurate enough for the limited time of this study.

Calibration of the lower level model- choice of parameters
The parameter for the logit model for the departure time choice was set to \( \mu = -0.01 \). This value was chosen after several parameters were tested, based on the times that the model calculated between specific Origin-Destinations, on peak and off-peak. This was done in combination with adjusting the scaling factor for the Origin-Destination matrix (since as mentioned before the Origin-Destination data available represent all the commuters, but of course not all of them travel by car, there may be more than one travellers per car and/or this commuting travel takes place on more than one hours in the morning, the peak occurring between 8.00-9.00. The travel times used for comparison with the modelled travel times were taken from the site of Tripcast, which takes into account the effect of congestion on travel times. The travel times used for on-peak were calculated for departure at 8.00, whereas for off-peak departure at 7.00.

4.3. Choices for the Upper level
As identified in chapter 2.5, the most important objectives that are pursued in most pricing schemes around the world are Congestion Relief and Environmental Protection. In line with these findings, these 2 objectives were considered for the case study. In addition, 2 different pricing measures are to be examined in association with the aforementioned objectives.

The first measure to be examined is cordon pricing. The setup for this measure is the city of Amsterdam. The cordon pricing is applicable only on peak and on all the inbound links for the city centre. The municipality of Amsterdam is responsible for setting the price for a cordon pricing toll. The fee will be paid per entry in the cordon.
The objective of the Municipality of Amsterdam is to minimize the emissions inside the city of Amsterdam during on-peak and will be calculated as follows: The loads on links inside the city of Amsterdam will be calculated, as a result of the lower level model, as well as the v/c ratios (load to capacity of each link). This will be used in the following equation as a measure of congestion, since higher congestion has a bigger effect on the emissions (stop and start). However, low congestion levels also yield high emissions, since low congestion means higher speeds for the cars, which again mean high emissions. Based on the analysis of Wismans (2012) it was decided that the objective function for the Municipality of Amsterdam should be formulated as follows:

\[ E = \sum_{i} \frac{v_i}{c_i} * v_i * d_i * \kappa, \text{ with } \frac{v}{c} = \{\max(0.5, \frac{v}{c})\} \]

where \( \kappa \) is an emission factor, equal for all links and \( \kappa = 210 \text{grCO}_2 / \text{veh.km} \), as used in the TREMOVE model for the Netherlands (CEDelft, Infras, & FraunhoferISI, 2011), \( v_i \) the flow on
each link, \( d_i \) the length of the link and \( c_i \) the capacity of each link. The v/c ratio is taken equal to 0.5 for low congested links, so as to take into account the effect that low congestion also leads to high emissions. The emissions were then converted to €, with a price of 56 €/tonne CO\(_2\) (CE Delft, 2008).

The second measure to be examined is the kilometre charge. Since there are not many examples of kilometre charge worldwide and it is a pricing measure currently under examination from the government of Netherlands, it is considered as an interesting measure to examine. The measure is set by the government of the Netherlands and it is applicable on all the highways, as seen in Figure 14.

The objective of the Government will be to minimize the Total Travel Time over the whole network on-peak. The kilometre charge will be applied on-peak so as to try to force users not only to change their route but also to change departure time. The objective will be calculated as follows:

\[
TTT = \sum TT_i \ast v_i, \text{ where } TT_i \text{ is the travel time on link } i \text{ and } v_i \text{ the flow on the respective link.}
\]
A third stakeholder is also considered in the upper level, the ANWB. According to their site: “The Royal Dutch Touring Club ANWB offers a wide range of services related to roadside assistance and medical and repatriation assistance abroad, legal assistance, travel, information products, insurances, selling travel related products and many other products and services in the areas of recreation, tourism and mobility. Furthermore, the ANWB is active in lobbying in the fields of driving, mobility, travel and recreation.” (ANWB website, 2013). ANWB will be the stakeholder representing the users. This stakeholder cannot control a pricing measure but can influence the decision process that is portrayed in the upper level. This will be modelled with the help of the veto player notion. In game theory, a veto player is a player that any coalition that does not include him has no value and therefore cannot be formed. If this stakeholder agrees with a pricing scheme, it will be a part of the coalition (although it will not bring any value to the coalition) and therefore will not get any pay-off. Accordingly, in the non-cooperative case, if the objective of this stakeholder is not fulfilled, then the current price vector cannot be accepted, needs to be updated and consequently the whole procedure will be updated etc.

The ANWB will veto or accept a solution according to the user surplus stemming from that solution. The user surplus is calculated as the monetized net balance between the time benefits and the out-of-pocket costs. As stated before, the only extra costs and therefore the only out-of-pocket costs that will be considered will be the costs of the pricing measures. A solution will be acceptable if the user surplus is positive.

The objective of ANWB is: \[ U = (TTT_i - TTT_0) - \left( \sum c_{cor} f_r \theta_r + \sum c_{km} v_i d_i \theta_i \right) \]

The first term of the equation \((TTT_i - TTT_0)\) represents the time benefits of each pricing scenario \(i\) compared to the zero case, whereas the second term \(\sum c_{cor} f_r \theta_r + \sum c_{km} v_i d_i \theta_i\) represents the total amount of money paid for the road pricing measures. \(\sum c_{cor} f_r \theta_r\) represents the amount of money paid for cordon pricing, whereas \(\sum c_{km} v_i d_i \theta_i\) represents the total amount of money paid for kilometre charge.

In the case study, the prices that will be given to the pricing measures are as follows:

<table>
<thead>
<tr>
<th>Pricing Measure</th>
<th>Off Peak</th>
<th>On Peak</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kilometer charge</td>
<td>0</td>
<td>0.03, 0.06, 0.09, 0.12 € per kilometre</td>
</tr>
<tr>
<td>Cordon pricing</td>
<td>0</td>
<td>1, 2, 3, 4 €, paid per crossing</td>
</tr>
</tbody>
</table>
The choices for the upper level are summarized in Table 13:

<table>
<thead>
<tr>
<th>Stakeholder</th>
<th>Objective</th>
<th>Measure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Municipality of Amsterdam</td>
<td>Minimize emissions during peak hours</td>
<td>Cordon pricing-time differentiated (On-peak/Off-peak)</td>
</tr>
<tr>
<td>Government</td>
<td>Minimize Total Travel Time during peak hours</td>
<td>Km-charging</td>
</tr>
<tr>
<td>ANWB</td>
<td>Positive User Surplus (monetized net balance between time benefits and out-of-pocket costs)</td>
<td>Veto power</td>
</tr>
</tbody>
</table>

The analysis will try to answer 2 basic questions. In the first part concerning the effects of each pricing measure on the network will be examined, namely on the Total Travel Time over the network and the emissions in the inner city of Amsterdam. As secondary effects on the network the v/c ratios (ratio of load of the link to the capacity of the link, signifying the occupancy of links) and the links used will be calculated, in order to give a better insight on the users’ choices. The second part will examine the combined effect of both measures and try to answer the questions whether cooperation or competition between the stakeholders yields better results, which are this solutions and whether these pricing schemes will be accepted from the users’ stakeholder, the ANWB.

For the second part two cases will be examined: the non-cooperative and the cooperative case. In the non-cooperative case each stakeholder decides individually his strategy, without knowing the moves of the other stakeholders, only how they affect their objectives. Their goal is to maximize their individual profit. The stakeholders are involved in a Nash game. Equilibrium is reached when no stakeholder can improve their profit without leaving another stakeholder worse-off. It can be said that each stakeholder is solving his own bi-level program simultaneously with the other stakeholders’ bi-level programs.

In the cooperative case, the stakeholders reach an agreement first before determining their price. Again their goal is to maximize their own profit, but this time knowing what the other stakeholders will do, by communicating and eventually by maximizing their combined profit. It is assumed of course that no stakeholder goes into coalition if his personal gain is not greater than or at least equal to the profit in the non-cooperative case. Mathematically, when a coalition is formed, the bi-level program can be seen as a traditional one leader-multi follower (Stackelberg game) bi-level program, but this time having the coalition as the leader.
25 different pricing scenarios will be examined, with one being the zero case scenario, where no measure is applied, and the other 24 different combinations of the aforementioned prices for each respective pricing measure.

<table>
<thead>
<tr>
<th>Table 14, Pricing scenarios</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pricing scenario</td>
</tr>
<tr>
<td>Km charge (€/km)</td>
</tr>
<tr>
<td>Cordon Pricing (€)</td>
</tr>
</tbody>
</table>

A summary of the choices for this case study’s bi-level program is shown below in Figure 15:

Figure 15, Overview of choices for the case study


4.4. Conclusions

The case study to be examined is the extended Randstad area. One user class will be modelled, the commuters, using a simple MNL model for users to choose when they want to travel (on-peak or off-peak) and then a Deterministic User Equilibrium Assignment will be used in order to assign users to their routes. These assumptions were deemed sufficient in order to examine the game theoretic approach to multi-stakeholder road pricing. For the upper level 2 stakeholders will be examined that control different pricing measures; the Government controlling a kilometre charge on highways on-peak and the Municipality of Amsterdam controlling a cordon pricing scheme, applicable also on-peak. Their respective objectives are to minimize Total Travel Time and to minimize emissions. ANWB is used as the stakeholder representing users. They cannot control any pricing measure, but have an effect on the pricing scheme, so they are modelled as a veto player. Their objective is to have a positive User Surplus.
5. Presentation of the Results

This chapter includes the presentation and the analysis of the results of the case study model. As a first step the zero case is presented, where no pricing measure is applied. This case will serve as an indication for the effect of the pricing measures in the subsequent pricing scenarios. Firstly the effect of each pricing measure on the users’ choices and the objectives is examined, as well as some secondary network indicators, such as link occupancy, denoted by the v/c ratio and number of links used, in order to better understand the processes taking place. Afterwards, the game theoretic approach is applied to determine whether cooperation or competition between the stakeholders imposing the road pricing measures (the Dutch government and the Municipality of Amsterdam) is more beneficial and how the extra value created in the cooperative case, if so, can be allocated based on the Shapley value. In the end the users’ acceptance is examined with the application of the veto player notion and the value created is again redistributed using the Shapley value, in this case to the 2 aforementioned stakeholders, as well as the ANWB (the users’ stakeholder).

5.1. Zero case

First, the case where no pricing measures are applied is examined, in order to establish a baseline for comparison with the pricing scenarios, as well as to examine whether the model produces realistic results. For the zero case, users still choose their departure time. The table below presents the findings for the zero case in terms of v/c ratio. This ratio is calculated as the ratio of flow on the link to the capacity of that link.

<table>
<thead>
<tr>
<th>Indicators</th>
<th>On-Peak</th>
<th>Off-Peak</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average v/c ratio on Highways</td>
<td>0.401</td>
<td>0.285</td>
</tr>
<tr>
<td>Average v/c ratio on Other roads</td>
<td>0.649</td>
<td>0.499</td>
</tr>
<tr>
<td>Number of Highway links used</td>
<td>461</td>
<td>442</td>
</tr>
<tr>
<td>Number of Other roads used</td>
<td>369</td>
<td>295</td>
</tr>
<tr>
<td>Highways with more than 0.5 v/c ratio</td>
<td>30.80%</td>
<td>16.29%</td>
</tr>
<tr>
<td>Other roads with more than 0.5 v/c ratio</td>
<td>57.45%</td>
<td>47.12%</td>
</tr>
</tbody>
</table>

As expected, the effect of on link occupancy is greater during the peak hours and especially on the smaller roads, which have lower capacities. However, highways are also highly occupied, as can be seen in Figure 16. During off-peak (Figure 17), the roads are less utilized and a smaller number of links is occupied. However, close to half of the other roads are heavily utilized (0.5 and more v/c ratio). The roads that are still near or over capacity are the ones surrounding and inside the bigger cities and the highway close to Schiphol (centroid 26).

For this section and the following ones, illustrative maps of the occupancy of the links of the network are provided in the Appendix 9.2.
Figure 16, Zero case congestion, on-peak

Figure 17, Zero case congestion, off-peak
The general assumption depicted from the results of the zero case is that the highways as well as the smaller roads in and around the main cities are highly occupied, some even exceeding capacity during on-peak, whereas off-peak they are in a lesser extend occupied and in some cases there are roads that are not used. Based on these findings it is understood that pricing measures can be used as a traffic management measures, firstly to force users to change their time of travel so the peak will be smoothed. Secondly, there are several roads that are not used and a pricing measure that will force users to change their route might prove beneficial, at least for the spatial spread of traffic (more roads used and less congestion on the main roads).

5.2. Application of Km charge

Effect on Route Choice
The effect of km charge is quite important on route choice, as it can be measured in terms of number of links used. On-peak, when the km charge takes effect, the use of highways is dropping, whereas it is increasing during off-peak. However the amount of highways abandoned is much more significant than that of the amount increasing during off-peak. Accordingly, the amount of smaller roads used is increasing significantly on-peak and to a lesser extend off-peak. Of course, it is increasing in both time periods, since the km charge forces users out of the highways and on to the smaller roads.

Table 16, Number of links used with km charge, on-peak

<table>
<thead>
<tr>
<th>Pricing scenario</th>
<th>1</th>
<th>6</th>
<th>11</th>
<th>16</th>
<th>21</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Highway links used</td>
<td>461</td>
<td>439</td>
<td>392</td>
<td>376</td>
<td>368</td>
</tr>
<tr>
<td>Number of Other roads used</td>
<td>369</td>
<td>593</td>
<td>659</td>
<td>667</td>
<td>719</td>
</tr>
</tbody>
</table>

Table 17, Number of links used with km charge, off-peak

<table>
<thead>
<tr>
<th>Pricing scenario</th>
<th>1</th>
<th>6</th>
<th>11</th>
<th>16</th>
<th>21</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Highway links used</td>
<td>442</td>
<td>450</td>
<td>451</td>
<td>452</td>
<td>453</td>
</tr>
<tr>
<td>Number of Other roads used</td>
<td>295</td>
<td>311</td>
<td>319</td>
<td>324</td>
<td>325</td>
</tr>
</tbody>
</table>

Effect on Total Travel Time
The solution that minimizes the Total Travel Time over the network on-peak would be a charge of 0.03 €/km. This will lead to a decrease in Total Travel Time on-peak of approximately 2% (146 685 veh.hours with the km charge in comparison to 149 419 veh.hours with no kilometre charge). This difference leads however to an increase of the Total Travel Time during the off-peak and as a result in an increase in the overall Total Travel Time.
All the other scenarios lead to an increase in Total Travel Time, both on-peak and as a total, because although a small percentage of users consider changing their departure time, most of them decide to travel on-peak but from a different route. Since the highways are tolled, users shift to smaller roads which have less capacity and speed limits, and therefore higher travel times. This additional time cost though is less than the additional cost stemming from the kilometre charge they would have to face if travelling from a highway and it is still less than the penalty of €40 so as to convince them to switch to the off-peak.

![Total Travel Time for km charge](image)

**Figure 18, Total Travel Time when imposing kilometre charge**

**Effect of km charge on link occupancy**

As expected, km charge minimizes significantly the occupancy on the highways during the on-peak. During the off-peak the occupancy is increasing on highways, but not significantly. On the other hand, smaller roads get more used, with a percentage of links having an average ratio equal or more than 0.5 close or over 50% for both on-peak and off-peak, meaning links are approaching capacity. It should be noted here that on scenario 6, where the km charge is €0.03 the v/c ratio is the lowest one for on-peak. This is mainly attributed to the fact that the number of roads that are used increase significantly compared to the previous scenario (Table 16) and consequently the average occupancy of each road is dropping, since the amount of users can spread to more routes.
Table 18, v/c ratio of links used with km charge, on-peak

<table>
<thead>
<tr>
<th>Pricing scenario</th>
<th>1</th>
<th>6</th>
<th>11</th>
<th>16</th>
<th>21</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average v/c ratio on Highways</td>
<td>0.401</td>
<td>0.287</td>
<td>0.258</td>
<td>0.239</td>
<td>0.221</td>
</tr>
<tr>
<td>Average v/c ratio on Other roads</td>
<td>0.649</td>
<td>0.520</td>
<td>0.562</td>
<td>0.597</td>
<td>0.582</td>
</tr>
<tr>
<td>Highways with more than 0.5 v/c ratio</td>
<td>30.80%</td>
<td>16.40%</td>
<td>10.71%</td>
<td>8.78%</td>
<td>6.52%</td>
</tr>
<tr>
<td>Other roads with more than 0.5 v/c ratio</td>
<td>57.45%</td>
<td>48.23%</td>
<td>52.35%</td>
<td>53.82%</td>
<td>57.87%</td>
</tr>
</tbody>
</table>

Table 19, v/c ratio of links used with km charge, off-peak

<table>
<thead>
<tr>
<th>Pricing scenario</th>
<th>1</th>
<th>6</th>
<th>11</th>
<th>16</th>
<th>21</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average v/c ratio on Highways</td>
<td>0.285</td>
<td>0.301</td>
<td>0.312</td>
<td>0.321</td>
<td>0.332</td>
</tr>
<tr>
<td>Average v/c ratio on Other roads</td>
<td>0.499</td>
<td>0.511</td>
<td>0.518</td>
<td>0.529</td>
<td>0.544</td>
</tr>
<tr>
<td>Highways with more than 0.5 v/c ratio</td>
<td>16.29%</td>
<td>18.67%</td>
<td>20.80%</td>
<td>21.06%</td>
<td>22.08%</td>
</tr>
<tr>
<td>Other roads with more than 0.5 v/c ratio</td>
<td>47.12%</td>
<td>49.84%</td>
<td>49.85%</td>
<td>50.16%</td>
<td>50.31%</td>
</tr>
</tbody>
</table>

Effect on Departure Time
The average Origin-Destination split on-peak and off-peak does not almost change at all. However, in order to better assess the effect of the kilometre charge on departure time choice, 4 Origin-Destination pairs have been selected. These pairs differ in distance and whether they pass through Amsterdam or not. This second fact is not of importance for the cases when only kilometre charge is imposed, but these results will be used as reference for the case of only cordon pricing taking effect.

Rotterdam to Utrecht
The first pair to be examined is Rotterdam to Utrecht, a medium sized distance travel (56 km) that do not pass from Amsterdam. It can be seen that for small prices of kilometre charge users keep travelling on-peak. However for higher prices, the split becomes equal and for 0.12 € there are more people travelling off-peak.
**Rotterdam to Utrecht**

This Origin-Destination pair is of bigger distance than the above (75.41 km), that also carries a high amount of users. This Origin-Destination has as an end destination Amsterdam (this will be used further down in the analysis of the results). In contrast to the pair Rotterdam-Utrecht, smaller prices are effective to convince users to change their departure time. This can be explained as follows: The cost for travelling off-peak is equal to the cost of travel time plus the penalty for changing to off-peak, which is 40 €. In order for that option to be more attractive, since the savings from travel time cannot compensate to that amount (the change in travel times would have to be around 2 hours, since Value of time is 19 €/h), the additional charge of the pricing measure has to be high enough. This can be the case for higher distances and for higher prices.

**Rotterdam to Amsterdam**

This Origin-Destination pair is of bigger distance than the above (75.41 km), that also carries a high amount of users. This Origin-Destination has as an end destination Amsterdam (this will be used further down in the analysis of the results). In contrast to the pair Rotterdam-Utrecht, smaller prices are effective to convince users to change their departure time. This can be explained as follows: The cost for travelling off-peak is equal to the cost of travel time plus the penalty for changing to off-peak, which is 40 €. In order for that option to be more attractive, since the savings from travel time cannot compensate to that amount (the change in travel times would have to be around 2 hours, since Value of time is 19 €/h), the additional charge of the pricing measure has to be high enough. This can be the case for higher distances and for higher prices.
Rotterdam to Alkmaar

This Origin-Destination pair is a long-distance travel (109.15 km). The explanation above can be seen that holds for this Origin-Destination pair. Since the distance travelled is high, and it is observed that users prefer to travel from highways, the additional cost from the kilometre charge is high enough so as to convince users to switch from on-peak to off-peak and with a smaller price (0.06 € compared to 0.09 € for the pair Rotterdam-Amsterdam and 0.12 € for the Rotterdam to Utrecht Origin-Destination pair).

![Rotterdam to Alkmaar On peak-off peak split for kilometre charge](image)

Utrecht to Zaanstad

The last pair to be examined is Utrecht to Zaanstad, an average sized distance Origin-Destination pair that passes through Amsterdam. This Origin-Destination pair yields almost the same results as the Rotterdam to Utrecht pair, and the effect is even smaller.

![Utrecht to Zaanstad On peak-off peak split for kilometre charge](image)
**Effect on Emissions**

The kilometre charge has an increasing effect on the emissions in the inner-city of Amsterdam. This effect is due mainly to the fact that users shift their routes from the highways to the inner roads, which leads to users using the roads that pass through Amsterdam and consequently increasing the congestion on the roads and eventually the emissions.

---

**Figure 23**, Emissions calculated when imposing a kilometre charge

---

**5.3. Application of Cordon Pricing**

**Route Choice**

As it can be seen from Table 20 and Table 21 below, cordon pricing has a limited effect on the route choice. When cordon pricing takes effect, highways are not affected in terms of number of links used, and some smaller roads that were not used before are used in the scenarios of cordon pricing application. However this increase in the amount of links is not significant, both on-peak and off-peak.

**Table 20, Number of links used with cordon pricing, on-peak**

<table>
<thead>
<tr>
<th>Pricing scenario</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Highway links used</td>
<td>461</td>
<td>461</td>
<td>461</td>
<td>461</td>
<td>461</td>
</tr>
<tr>
<td>Number of Other roads used</td>
<td>369</td>
<td>372</td>
<td>372</td>
<td>372</td>
<td>372</td>
</tr>
</tbody>
</table>

---
Table 21, Number of links used with cordon pricing, off-peak

<table>
<thead>
<tr>
<th>Pricing scenario</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Highway links used</td>
<td>442</td>
<td>442</td>
<td>442</td>
<td>442</td>
<td>442</td>
</tr>
<tr>
<td>Number of Other roads used</td>
<td>295</td>
<td>302</td>
<td>302</td>
<td>302</td>
<td>302</td>
</tr>
</tbody>
</table>

**Effect on Total Travel Time**
The effect of cordon pricing network wide in terms of Total Travel Time is beneficial during on peak. Compared to the zero case, all prices of cordon pricing yield better results in terms of Total Travel Time. The price that minimizes the Total Travel Time is €2. The differences in Total Travel Time are shown in Table 22. During the off-peak Total Travel Time increases because of the amount of people switching time periods from the on-peak to off-peak.

Table 22, Relative Differences on Travel time in respect to cordon pricing application

<table>
<thead>
<tr>
<th>Cordon Pricing (Price in €)</th>
<th>Rel. Difference in Total Travel Time On Peak (%)</th>
<th>Rel. Difference in Total Travel Time Off Peak (%)</th>
<th>Rel. Difference in Total Travel Time (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>-4.69</td>
<td>2.81</td>
<td>-2.37</td>
</tr>
<tr>
<td>2</td>
<td>-5.13</td>
<td>2.96</td>
<td>-2.63</td>
</tr>
<tr>
<td>3</td>
<td>-5.11</td>
<td>3.09</td>
<td>-2.57</td>
</tr>
<tr>
<td>4</td>
<td>-5.05</td>
<td>3.05</td>
<td>-2.54</td>
</tr>
</tbody>
</table>

**Effect of cordon pricing on link occupancy**
Cordon pricing has not significant effect on link occupancy. As a general observation it marginally increases off-peak both on highways and smaller roads, whereas it limitedly decreases during on-peak.

Table 23, v/c of links used with cordon pricing, on-peak

<table>
<thead>
<tr>
<th>Pricing scenario</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average v/c ratio on Highways</td>
<td>0.401</td>
<td>0.395</td>
<td>0.394</td>
<td>0.393</td>
<td>0.393</td>
</tr>
<tr>
<td>Average v/c ratio on Other roads</td>
<td>0.649</td>
<td>0.629</td>
<td>0.629</td>
<td>0.626</td>
<td>0.627</td>
</tr>
<tr>
<td>Highways with more than 0.5 v/c ratio</td>
<td>30.80%</td>
<td>30.59%</td>
<td>30.59%</td>
<td>30.59%</td>
<td>30.59%</td>
</tr>
<tr>
<td>Other roads with more than 0.5 v/c ratio</td>
<td>57.45%</td>
<td>54.03%</td>
<td>53.76%</td>
<td>54.03%</td>
<td>54.03%</td>
</tr>
</tbody>
</table>
Table 24, v/c ratio of links used with cordon pricing, off-peak

<table>
<thead>
<tr>
<th>Pricing scenario</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average v/c ratio on Highways</td>
<td>0.285</td>
<td>0.293</td>
<td>0.293</td>
<td>0.293</td>
<td>0.293</td>
</tr>
<tr>
<td>Average v/c ratio on Other roads</td>
<td>0.499</td>
<td>0.508</td>
<td>0.509</td>
<td>0.509</td>
<td>0.510</td>
</tr>
<tr>
<td>Highways with more than 0.5 v/c ratio</td>
<td>16.29%</td>
<td>17.19%</td>
<td>17.19%</td>
<td>17.65%</td>
<td>17.65%</td>
</tr>
<tr>
<td>Other roads with more than 0.5 v/c ratio</td>
<td>47.12%</td>
<td>48.01%</td>
<td>47.68%</td>
<td>48.68%</td>
<td>47.35%</td>
</tr>
</tbody>
</table>

**Effect on Departure Time**

Although the kilometre charge had an effect on departure time choice, the cordon pricing has almost no effect. The price of the cordon pricing is not enough to force commuters to switch off-peak which imposes an extra cost (penalty) of €40 more. Again the time benefits from travelling off-peak are not enough to offset the effect of the penalty and the extra cost of the cordon pricing. However, slight differences can be observed, but not of the same magnitude as the kilometre charge.

For all the cases, except for the case of Rotterdam to Amsterdam, on-peak users actually increase. One explanation that can be given for that is that users that actually have as destination Amsterdam are most affected from the cordon pricing, although very slightly. Because of those travellers changing departure time, some routes become more attractive (less congested) on-peak and actually attract users from other Origin-Destination pairs to change departure choice from off peak to on peak this time.

Table 25, Departure time split for specific Origin-Destination pairs

<table>
<thead>
<tr>
<th>Utrecht to Zaanstad</th>
<th>Rotterdam to Alkmaar</th>
<th>Rotterdam to Amsterdam</th>
<th>Rotterdam to Utrecht</th>
</tr>
</thead>
<tbody>
<tr>
<td>On-Peak(%)</td>
<td>Off-Peak(%)</td>
<td>On-Peak(%)</td>
<td>Off-Peak(%)</td>
</tr>
<tr>
<td>58.07</td>
<td>41.93</td>
<td>58.21</td>
<td>41.79</td>
</tr>
<tr>
<td>58.43</td>
<td>41.57</td>
<td>58.42</td>
<td>41.58</td>
</tr>
<tr>
<td>58.43</td>
<td>41.57</td>
<td>58.41</td>
<td>41.59</td>
</tr>
<tr>
<td>58.45</td>
<td>41.55</td>
<td>58.43</td>
<td>41.57</td>
</tr>
<tr>
<td>58.46</td>
<td>41.54</td>
<td>58.43</td>
<td>41.57</td>
</tr>
</tbody>
</table>

**Effect on Emissions**

The effect of cordon pricing on emissions during on-peak is much more beneficial than of the kilometre charge, as it is to be expected, although the relative difference observed is around 3% for the highest cordon pricing (€4). This small difference can be mainly attributed to the fact that the prices of the cordon pricing are not high enough to convince a big percentage of users
to change to the off-peak. Off peak the emissions marginally increase, because of the people switching from on peak to off peak, however as mentioned before this percentage is not big. The overall emissions marginally increase (on average 0.7% for every scenario compared to the zero case).

**Figure 24**, Effect of cordon pricing on emissions, on peak

**Figure 25**, Effect of cordon pricing on emissions for all time periods
5.4. Game Theoretic Results

In this section the results of the game theoretic approach are presented. Based on the model results, Total Travel Time and Emissions on-peak are calculated and then transformed to monetary units. Firstly, a simple 2-persons game is examined, with only the Municipality of Amsterdam and the Dutch government acting, and both cooperative and non-cooperative solutions are presented (Chapter 5.4.1). As explained before, the Municipality of Amsterdam imposes the cordon pricing on-peak and seeks to minimize the emissions inside the city centre on-peak, whereas the Dutch government imposes a kilometre charge on the highways on-peak and seeks to minimize the Total Travel Time over the network on-peak as well. After that, in Chapter 5.4.2, the game also involves ANWB as a veto player, and the game theoretic solutions are reconsidered. For both games the core solutions and the Shapley values are calculated.

5.4.1. Game without ANWB

Non-Cooperative case

If both the stakeholders set their prices individually, without prior knowledge of the other stakeholder’s strategy, the equilibrium reached will be as shown in Table 26. In this scenario no stakeholder can improve their gains compared to the zero case without leaving the other stakeholder worse off. The pricing scenario that comprises the equilibrium point is **Scenario 5**, with no kilometre charge and a cordon pricing of €4 per crossing.

<table>
<thead>
<tr>
<th>Km Charge (in €)</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>31</td>
<td>40</td>
<td>42</td>
<td>49</td>
<td>143,310</td>
</tr>
<tr>
<td>0.03</td>
<td>-123</td>
<td>-103</td>
<td>-49</td>
<td>-25</td>
<td>-11</td>
<td></td>
</tr>
<tr>
<td>0.06</td>
<td>-368</td>
<td>-255</td>
<td>-230</td>
<td>-194</td>
<td>-174</td>
<td></td>
</tr>
<tr>
<td>0.09</td>
<td>-558</td>
<td>-440</td>
<td>-410</td>
<td>-278</td>
<td>-283</td>
<td></td>
</tr>
<tr>
<td>0.12</td>
<td>-634</td>
<td>-606</td>
<td>-518</td>
<td>-504</td>
<td>-427</td>
<td></td>
</tr>
</tbody>
</table>

Table 26, Results for the non-cooperative case (TTT gains in €\ Emission gains in €)
**Cooperative case**

In the case where the stakeholders can jointly decide their strategy before imposing their prices, the goal is to set prices that will improve their joint gains. In this case the solution is not the same as in the cooperative case. The best strategy would be no km charge and a cordon pricing of 2 € (*Scenario 3*). For this scenario the government is better off than the non-cooperative case. The Total Travel Time gains in this case are €145 536, whereas for the non-cooperative equilibrium it is €143 310, which means a benefit of 2 226 € in travel time savings. The Municipality of Amsterdam however is left worse off. The emission gains for this pricing scheme are equal to €40, whereas for the non-cooperative solution they are €49, so a loss of 9 €. In order for the municipality of Amsterdam to have an incentive to stay in the coalition the government should reimburse them with an amount at least equal to their loss compared to the non-cooperative case, so €9 or more. With a reimbursement of €9, the municipality of Amsterdam reaches its equilibrium point and has no incentive to leave the coalition and the government is still left better off with an improved objective of 2 226-9=€2 217. Even bigger refund can be given to the Municipality of Amsterdam, to strengthen the coalition.

**Table 27, Results for the cooperative case**

<table>
<thead>
<tr>
<th>Km Charge (in €)</th>
<th>Cordon Pricing (in €)</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>133 191</td>
<td>145 575</td>
<td>145 117</td>
<td>143 358</td>
<td></td>
</tr>
<tr>
<td>0.03</td>
<td>51 825</td>
<td>17 715</td>
<td>48 645</td>
<td>41 777</td>
<td>-10 314</td>
<td></td>
</tr>
<tr>
<td>0.06</td>
<td>-510 093</td>
<td>-490 500</td>
<td>-463 173</td>
<td>-447 629</td>
<td>-454 062</td>
<td></td>
</tr>
<tr>
<td>0.09</td>
<td>-902 067</td>
<td>-821 623</td>
<td>-838 736</td>
<td>-800 183</td>
<td>-614 843</td>
<td></td>
</tr>
<tr>
<td>0.12</td>
<td>-1 241 526</td>
<td>-1 191 972</td>
<td>-1 145 167</td>
<td>-1 242 414</td>
<td>-1 138 844</td>
<td></td>
</tr>
</tbody>
</table>

**The core**

This cooperative solution, although it optimizes the joint benefit, however does not lie in the core, because one stakeholder (the Municipality of Amsterdam) is worse-off than the cooperative solution, so it needs some kind of reimbursement, until at least equal to the amount that the Municipality is worse off, so they can be pursue to form the coalition.

**Shapley value**

Although it seems intuitively that with a reimbursement of €9, the Municipality of Amsterdam would be to its previous state so it would be fine, if we assess what the Municipality actually brings to the table of the coalition, the contribution is far bigger.
We assume that each stakeholder chooses their pricing strategy according to their individual objective, but since their action produces an effect on the other objective as well, the collective objective is assessed. The value of the individual stakeholders and their coalition is shown below:

\[ v(S) = \begin{cases} 
51,825, & (G) \\
143,358, & (M) \\
145,575, & (G,M) \\
0, & \emptyset 
\end{cases} \]

Where \((G)\) is the case of only the government applying a road pricing measure, \((M)\) is the case for the Municipality of Amsterdam and \((G,M)\) the coalition between the Government and the Municipality of Rotterdam and \(v(S)\) is the function assigning the gains for each coalition (calculated as the gains in € compared to the zero case), based on the results generated before from the lower level model.

The Average Marginal Contributions (Shapley value) are shown below.

<table>
<thead>
<tr>
<th>Stakeholder</th>
<th>Marginal Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>G</td>
<td>27,021</td>
</tr>
<tr>
<td>M</td>
<td>118,554</td>
</tr>
<tr>
<td><strong>Total value added</strong></td>
<td><strong>145,575</strong></td>
</tr>
</tbody>
</table>

It is own that the actual worth that the Municipality of Amsterdam brings to the coalition is far more significant that initially thought. With this method, the Municipality of Amsterdam has now a big negotiation asset in order to improve its position.

### 5.4.2. Incorporation of User Acceptance-Game with ANWB

As it can be seen from the diagram below, user surplus is only positive for the first 5 scenarios (€0 km charge and cordon pricing between €0-4). This means that the solutions that will be accepted are only the solutions of pricing scenarios numbers 1-5.
Non-Cooperative case

The non-cooperative solution is among these scenarios mentioned above. This means that the ANWB would not object to that pricing schemes, since the amount of money paid for the pricing measures is less than the amount of money gained from the decrease in travel times, meaning that the user surplus is positive.

Cooperative case

Shapley value

In the cooperative scenario it gets a little bit more complicated. Since we have assumed that the ANWB is a veto player, they need a payoff in order to join the game. We know face a 3 person game. For this allocation again the notion of Shapley value will be used.

\[
v(S) = \begin{cases} 
0, & (G, A) \\
143 358, & (M, A) \\
145 575, & (G, M, A) \\
0, & \text{otherwise}
\end{cases}
\]
where \((G, A)\) is the coalition of the government and the ANWB, \((M, A)\) is the coalition of the Municipality of Amsterdam and ANWB and \((G, M, A)\) the coalition of all three stakeholders (Grand coalition).

In this case the set of solutions that can be applied are limited to the ones that user surplus is positive, otherwise ANWB vetoes. This means that the only coalitions that can be accepted are the ones that ANWB joins and any other action cannot be pursued, for example the government and the Municipality of Amsterdam cannot cooperate without the involvement of the ANWB.

In order to assess the payoff to each stakeholder, the marginal contribution of each stakeholder should be assessed, in other words the extra worth they bring to the coalitions formed before them. These marginal contributions are shown in Table 29.

<table>
<thead>
<tr>
<th>Stakeholder</th>
<th>Marginal Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>G</td>
<td>739</td>
</tr>
<tr>
<td>M</td>
<td>72 418</td>
</tr>
<tr>
<td>A</td>
<td>72 418</td>
</tr>
<tr>
<td>Total value added</td>
<td>145 575</td>
</tr>
</tbody>
</table>

The total value added is the same as before. However, now a third stakeholder is involved in the game and needs to get an allocation of this value. This leaves both the government and the Municipality worse off in terms of payoff; however with the involvement of the ANWB they ensure the acceptance of the public and consequently the success of the pricing scheme. However, both these stakeholders are left better off than the non-cooperative case.

If the Grand coalition is to be formed, this means that if the stakeholders eventually reach an agreement for a common strategy, each of the stakeholders above should get the aforementioned amounts of money from the extra value generated between the zero case scenario (no implementation of pricing scheme) and the implementation of scenario number 3 (0 km charge and €2 cordon pricing), which yields the best results for a joint objective.

What the Shapley value implies is that eventually the contribution of both ANWB and the Municipality of Amsterdam is far greater than identified before.
5.5. Conclusions

On a first stage, the effect of the pricing measures on the users’ choices was assessed. It was found that for the case of one-user class (commuters) the effect of kilometre charge on highways on Total Travel Time was determined as disadvantageous for Total Travel Time, because the km charge encourages people to leave the highways and move to smaller roads. The effect of km charge was smaller on departure time choice. Emissions were also negatively affected because of the kilometre charge, both on peak and off peak.

The effect of cordon pricing is of smaller magnitude for all users’ choices. The main effect of cordon pricing was the decrease of emissions in the city of Amsterdam, which was the main objective. Also cordon pricing seems to affect positively the Total Travel Time on peak and negatively off peak, yielding minor differences on the Total Travel Time for the whole period. Route choice is limitedly affected. Minor changes regarding the departure time split, mainly to the Origin-Destination pairs with destination Amsterdam, lead to minor changes in occupancy of the roads, decreasing on peak and increasing off peak.

On a second stage the game theoretic approach was applied. It was found that the non-cooperative and the cooperative solutions were different. The optimal cooperative solution was better in terms of the collective objective, however not both stakeholders were left better off, so they needed an incentive in order to join the coalition. The core did not exist, since the best solution for the coalition of the Government and the Municipality of Amsterdam yielded fewer gains for the Municipality. However, the Government could compensate the Municipality of Amsterdam, until the amount of gains they had in the non-cooperative case and be still left better-off. The Shapley value however allocated more compensation to the Municipality of Amsterdam than it was initially considered (the amount of money needed in order to reach at least the non-cooperative solution). Both these solutions were in the solution space of the ANWB, the stakeholder representing the users (the user surplus was positive). However, when applying the game theoretic framework and the notion of veto player, we face a 3 person game, and the Shapley value allocates an amount of value to the ANWB as well, leaving less for the other 2 stakeholders. However, with these allocations they were again left better off than the non-cooperative case.
6. Policy considerations

Game theory has been used in transportation analysis mainly to describe the interaction between the travellers (model interaction between the users in the lower level) or the travellers as a whole and one decision making authority (Hollander & Prashker, 2006; Fisk, 1984). There exists some research about competition between stakeholders in the upper level of transport problems (e.g. Dimitriou & Stathopoulos, 2011; Fisk, 1984; Hollander & Prashker, 2006). There is, however, limited research about the interaction between stakeholders involved in road pricing schemes and especially about the cooperative case (for example Ohazulike, 2009; Ohazulike, Bliemer, Still, & Berkum van, 2012; Smits, Bliemer, Verhoef, & van Arem, 2012; (Smits, Modelling Transport Pricing with Multiple Stakeholders. Working Paper: Methodology and a Case Study, 2012).

This research can be used from policy makers as an instrument for achieving broader social consensus regarding road pricing schemes, mainly before implementing them, so as to avoid delays during implementation and eventually underperformance of their respective objectives. Of course, game theory as a policy instrument has both positive and negative traits. In one hand, game theory can provide an excellent instrument for capturing interactions between the decision-making authorities and the stakeholders involved in pricing schemes. It can also be employed as a tool for giving all stakeholders affected an insight of the effects each one has on the decisions of the others. As shown in the case study before, the effect of joint application of different pricing measures has different effects than applying the pricing measures separately and the contribution of each pricing measure might be quite more significant than the effect on each stakeholder’s objective. The use of Shapley value can illustrate the actual contribution of each stakeholder’s in terms of value added to the common goal. On the other hand it is not easy to formulate the objective function of the coalition, especially if different objectives are involved.

Game theory uses the assumptions that the stakeholders will always play in a rational way and always has perfect information on the effects of the other stakeholders’ actions on their objective(s), which might not always be the case (Hermans, Cunningham, & Slinger, 2014). The assumption of complete information, which is also needed from the modeller, is not always easy to achieve since some stakeholders might not be willing to provide information over their strategies and goals.

In case of more than two stakeholders, which is usually the case, it might be difficult to determine the coalitions, the equilibrium points and the exact amount of reimbursements needed. In the case study examined in this report there existed only 2 stakeholders, which make it comparatively easier to identify which stakeholder should reimburse which one and by which amount. When more than 2 stakeholders exist however the side payments and their exact amount is difficult to identify, so as all stakeholders have an incentive to stay to the coalition. In
addition, since more than one coalition might exist, it becomes obvious that the solutions become more and more difficult to identify.

It can be said that the use of game theory in policy making gives a ‘hard’ side to a ‘soft’ science. Although policy making is an important aspect that affects everybody, people tend to be sceptical about processes that involve personal views and preferences. By applying game theory, although we should be very careful how to capture all these aforementioned preferences and views, and hard-coding them in mathematical terms, even the more sceptical stakeholders might be pursued, mainly because mathematics are considered the only universal language. Of course this can always work the other way around; one can argue that mathematics will never be able to sufficiently capture all the social interactions that might take place in such decision processes.

A model is always a simplistic representation of reality, which can be both good and bad. Good, because it can simplify complex situations to their main characteristics and give a simple overview of the problem and its solutions. However, because it is a simplistic view, it is not always obvious which is a main characteristic and which is not, and for some stakeholders something might be important and something that is not might be for somebody else. Multi-stakeholder decision processes include measurable and non-measurable objectives, hierarchies of stakeholders, and preferences over objectives, choices and dilemmas and several other aspects that are difficult to capture in a mathematical equation. Each stakeholder has different objectives and assigns different weight on each objective. A simplistic view of a model however is never the exact reality, rather than a balance between computational time and complexity on the one hand and main characteristics and expected accuracy on the other. Of course, always the results should be approached with caution and critical thought. A model can force the modeller to make a vague policy question more accurate, in order to capture it in a model (van der Hoorn & van Wee, 2013). However this exact thing can eventually lead to omissions and therefore not reliable results.

**Veto power**

In game theoretic terms, a veto player in a simple game is a player that belongs to all winning coalitions. Supposing there is a veto player, any coalition not containing a veto player is losing. This basically means that any solution that stems from a coalition that a veto player is not a part of, so this means that this solution is not of his best interest, it will not be accepted.

The veto notion as a means of modelling and incorporating user acceptance in the modelling process is considered as effective, as viewed from the case study. However this notion brings one additional issue, than the ones mentioned before. A veto power assigns power to a stakeholder that cannot control a pricing measure and its price, however has a great influence on the overall outcome (in the case study the acceptance of ANWB has a great influence on the effectiveness of the pricing scheme, although they do not control any pricing measure). This can
be considered a positive effect. However, on the other side of the coin, the veto power might give to that stakeholder excess power and influence that he/she might not possess.
7. Conclusions and Recommendations

7.1. Conclusions and Findings

The main objective of this thesis that was formulated at the beginning of this report is as follows: “Reformulation of the traditional bi-level program used for the road pricing problem to better fit in a multi-stakeholder environment (multi-leader multi-follower game) using game theory. In addition to that, exploration of how users’ acceptance can be incorporated in this bi-level game-theoretic formulation. Examination of whether game theory can be used in policy-making”.

Stakeholders and Road Pricing Theory

- Why road pricing?
- What examples of road pricing exist?
- What lessons can be learnt?

Road pricing is regarded as an efficient tool for internalizing external costs, costs that travellers might not be aware that they impose or they tend not to consider. These costs include congestion, emissions, noise, accident risk and road pavement damage. Each road pricing scheme consists of 3 main components. First, the pricing type of the measure, which can be one of area pass, cordon/zone charging, point based charge (e.g. tolls) and distance based charging. Secondly, the price level of each measure and finally the differentiation of the price, according to the vehicle type, user group, location of application of the pricing scheme and time of application. If the price remains the same is called flat, if there are some differentiations that are pre-determined it’s called variable and if the measure is dependent on the conditions of a specific instance (for example the actual levels of congestion) is called dynamic. From the international experience of road pricing it can be concluded that the main objectives observed are congestion relief, environmental protection and revenue growth. Other objectives observed were economic growth, health, liveability, safety, equity and future generations. The main pricing measures used are variable area pass, variable and dynamic cordon charging and flat or variable tolls. Distance based charging has not been yet extensively examined. The main stakeholders involved that can control the pricing measures are the government (regional or national, city councils and state agencies. Other stakeholders involved, that cannot control a pricing measure but can be of importance for the success of the scheme include Public Transport and Public Services, traveller organizations (motorists, cycling and pedestrian), environmental organizations and stakeholders of economic interest (financial institutions, retailers, manufacturers etc). An important factor of success for most of the pricing schemes that was identified is the acceptance of the travellers.
Explorative Phase

- How can the road pricing problem be represented (Bi-level formulation)?
- What is the difference between one stakeholder and multiple stakeholders?
- How can they interact with each other (competition or cooperation)-what is the game theory behind it?
- How can user acceptance be incorporated using game theory tools?
- What effects can be measured and how?

The road pricing can be represented as a bi-level program, having in the upper level the decision-making authority and in the lower level the users. The decision-making authority tries to optimize his/her objective(s), constrained by the reaction of the users in the lower level, who try to minimize their travel cost. The interaction between the upper and the lower level can be represented by a Stackelberg game, whereas the interaction between the users inside the lower level can be represented by a Nash non-cooperative game.

If more than one decision-making authorities (stakeholders) exist in the upper level the bi-level program needs to be reformulated. In the non-cooperative case, the authorities decide individually their strategy with a goal to maximize their own objective. It can be said that each stakeholder is solving his own bi-level program simultaneously with the other stakeholders’ bi-level programs. The stakeholders between them are also in a Nash non-cooperative game. In the cooperative case the stakeholders decide on a joint strategy before applying it, with a goal to maximize a common objective. There exist two kinds of cooperative games, the Non-Transferable Utility and the Transferable Utility games. Since in road pricing cases it is possible to have compensations and transfer of payments, this research focused on the TU games. The main solution concepts that exist for cooperative games are the core and the Shapley value. The core represents all the allocations of the gains achieved through the formation of a coalition that yield bigger gains for the stakeholders than in the non-cooperative case. If the core exists the stakeholders can form a coalition that they do not want to deviate from. There might exist more than one allocation though in the core. The Shapley value is an allocation method of the coalitional gain that assigns to each stakeholder its average marginal contribution to the coalition.

For this research, user acceptance was modelled in a game theoretic approach using the notion of a veto player. A veto player is any player that if he/she is not part of a coalition, then this coalition is losing, in other words it cannot be formed.

The effects are measurable indicators that help assess the fulfilment or not of the policy objectives set by the decision making authorities. These effects can be expressed in their respective measurement (for example time cost in minutes) or they can be transformed into monetary units, so they can be easily compared. Effects that can be measured from this bi-level process include accidents, emissions, noise, road pavement damage, time cost, user surplus and revenues generated.
Case study

Set-up

- Based on which case study- Which network to be chosen?
- What choices to be made for the lower level?
- Which stakeholders and objectives to be included in the upper level?
- What is needed (inputs and outputs) (data)?

Results

- What are the effects of the pricing measures on the users’ choices?
- What is the difference between the solutions for cooperation and competition between the stakeholders?
- Are these solutions accepted from the users?
- How can the gains be distributed to the stakeholders?
- What policy implication can be derived from these results

The case study that was examined is the extended Randstad area. One user class, the commuters was modelled, using a simple MNL model for users to choose when they want to travel (on-peak or off-peak) and then a Deterministic User Equilibrium Assignment was used in order to assign users to their routes. These assumptions were deemed sufficient in order to examine the game theoretic approach to multi-stakeholder road pricing. For the upper level 2 stakeholders were examined that could control different pricing measures; the Government controlling a kilometre charge on highways on-peak and the Municipality of Amsterdam controlling a cordon pricing scheme, applicable also on-peak. Their respective objectives were to minimize Total Travel Time and to minimize emissions. ANWB was used as the stakeholder representing users, which could not control any pricing measure, so was modelled as a veto player. Its objective was to have a positive User Surplus.

Firstly, it was found that for the commuters the effect of kilometre charge on highways on Total Travel Time was determined as disadvantageous for Total Travel Time, because the km charge encourages people to leave the highways and move to smaller roads. The effect of km charge was smaller on departure time choice. Emissions were also negatively affected because of the kilometre charge, both on peak and off peak. The effect of cordon pricing is of smaller magnitude for all users’ choices. The main effect of cordon pricing was the decrease of emissions in the city of Amsterdam, which was the main objective. Also cordon pricing seems to affect positively the Total Travel Time on peak and negatively off peak, yielding minor differences on the Total Travel Time for the whole period. Route choice is limitedly affected. Minor changes regarding the departure time split, mainly to the Origin-Destination pairs with destination Amsterdam, lead to minor changes in occupancy of the roads, decreasing on peak and increasing off peak.

Regarding the effect of pricing measures to different objectives and user choices, it is indicated that there is a strong connection between these three factors and they should be chosen carefully when setting up a new pricing scheme. However when more than one pricing schemes
exist, or more than one stakeholders impose different road pricing measures, even if their pricing measures might not be chosen for pursuing a specific objective, they might have an important effect on it (from the case study that was set up it was found that the best result in terms of Total Travel Time was in a scenario when no km charge was imposed but only cordon pricing, which was initially used in order to minimize emissions).

On a second stage the game theoretic approach was applied. It was found that the non-cooperative and the cooperative solutions were different. The optimal cooperative solution was better in terms of the collective objective, however not both stakeholders were left better off, so they needed an incentive in order to join the coalition. The core did not exist, since the best solution for the coalition of the Government and the Municipality of Amsterdam yielded fewer gains for the Municipality. However, the Government could compensate the Municipality of Amsterdam, until the amount of gains they had in the non-cooperative case and be still left better-off. The Shapley value however allocated more compensation to the Municipality of Amsterdam than it was initially considered (the amount of money needed in order to reach at least the non-cooperative solution). Both these solutions were in the solution space of the ANWB, the stakeholder representing the users (the user surplus was positive). However, when applying the game theoretic framework and the notion of veto player, we face a 3 person game, and the Shapley value allocates an amount of value to the ANWB as well, leaving less for the other 2 stakeholders. However, with these allocations they were again left better off than the non-cooperative case.

It can be concluded that the game theoretic framework is a promising solution concept for evaluating road pricing with multiple stakeholders. Since game theory is used to treat problems with multiple actors and model the interactions between them, road pricing is an ideal field for application. The game theoretic framework not only can show to stakeholders their potential effect in the outcomes of a road pricing scheme, it can also show whether they can improve their respective objectives by working alone or cooperating and if needed to cooperate, with which stakeholders they should do so.

The use of game theory for policy-making has both negatives and positives. On the positive side, it can be used to model the interactions between the stakeholders and can offer a more coded, stripped to the essentials process through mathematical equations. On the negative side it implies the rationality and total information which is not always easy to manage. In addition, all the objectives, beliefs, hierarchies, preferences, choices and dilemmas of the stakeholders is difficult to be captured in mathematical equations, or they will be so complex that the computational effort needed might be overwhelming.

The veto player notion is also suitable for incorporating users’ acceptance in the decision-making process, since users’ cannot be otherwise incorporated in the decision process since they do not control a pricing measure but their acceptance of the project is crucial for its implementation. However, the veto player concept might allocate more decision power to a stakeholder than they actual possess.
7.2. Recommendations

It is recommended that a further research in contacted for cases with more than 2 stakeholders and more complex pricing schemes, so as to effectively assess if game theory can efficiently tackle real life situations. Also the examination of different objectives or multiple objectives would also affect the outcomes of the games. It is highly recommended to asses the applicability of the game theoretic approach to multi-objective cases, so as to determine whether it is possible to determine the utility functions that are needed for game theory for complex structures.

This research focused on a simplified case study, in terms of transport model and the assessment of the game theoretic framework was not very much computationally intense. It is advised that this research is applied to more complex transport models (dynamic, multi-user class and multi-objective) so as to assess the applicability of game theory with more realistic transport reactions. In addition, the incorporation of different users choices might have a different effect on the outcomes (if users can also choose their mode or to stay home).

Since there was not used an optimization process, rather an examination of 24 discrete scenarios, an optimization process should be employed to check whether the game theoretic framework can work well along with optimization algorithms.

For policy-makers, it is recommended to use game theory with caution. Game theory can provide a tool for supporting decision-making but its results cannot be used as they are, without further analysis with other tools. It is also recommended that a re-evaluation of existing pricing schemes is made with game theoretic tools so as to see if this approach can yield the same results and consequently its reliability.

Regarding the veto player approach, an assessment should be made on whether there can be applied weights on the veto process, so these players do not get more power and influence than they might possess.
8. Bibliography

(2013, 11). Opgehaald van Tripcast: www.tripcast.nl


### 9. Appendix

#### 9.1. Overview of the existing pricing schemes

<table>
<thead>
<tr>
<th>City</th>
<th>Objectives</th>
<th>Network and Environment Effects</th>
<th>Pricing Measures</th>
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</table>
| Bergen   | Raise funds for road or PT investments in order to tackle the increasing traffic problems  
*(Revenue Growth-Congestion Relief)* | Number of accesses in the LTZ reduced by 25%, by 3% in the main streets of the city centre and roughly 70% unauthorized use of bus lanes  
The number of freight operators permits reduced by 27% and by 10% by total permits (operators plus citizens). | 24-hours flat toll (one trip/hour)-different for 2 vehicle categories (exemptions for electric vehicles, emergency vehicles, people with disability parking permit, busses and motorcycles/mopeds) |
| Bologna  | Decrease the number of vehicle km while providing the same level of service and to deploy less polluting "clean" vehicles  
*(Environmental Protection)* |                                                                                                                                                                                                                                    | Annual permits depending on the EURO norm, pay-to-access tickets (daily or for 4 days)                                                                                                           |
| Bristol  | Tackle congestion  
Improve road safety for all road users  
Improve air quality  
Improve access to job opportunities  
Help people to get to work and school efficiently  
Strengthen the local economy  
Improve quality of life  
*(Congestion Relief-Environmental Protection-Liveability-Economic Growth)* | 85% Reduction in vehicular traffic (from 2000 to 200 vehicles per day).  
An increase of 5% in total journeys terminating in the city centre by all modes  
A small reduction in overall traffic levels and delays between the inner and outer cordons, and only small changes outside the outer cordon  
Slight increase in orbital traffic between the cordons, with some localized changes that would require mitigation measures  
An increase in PT use of around 10%. | (Probably) a weekday morning road user charge                                                                                                                                   |
| Cambridge| Traffic Management  
*(Congestion Relief)* |                                                                                                                                                                                                                                    | One-off charge for driving into, out of or within Cambridge, weekdays morning peak, flat toll                                                                                                         |
| Durham   | Improve pedestrian safety  
Improve access for the disabled  
Enhance a world heritage site  
Sustain vitality of this part of the city centre  
*(Safety-Equity/Social Inclusion-Environmental Protection)* | Significant reduction in traffic levels and delays within the city centre  
An increase of 5% in total journeys terminating in the city centre by all modes  
A small reduction in overall traffic levels and delays between the inner and outer cordons, and only small changes outside the outer cordon  
Slight increase in orbital traffic between the cordons, with some localized changes that would require mitigation measures  
An increase in PT use of around 10%. | Morning peak hour Monday-Saturday flat toll, paid on exit from the area  
Exemptions: Residents, students, PT, Security-postal services, Emergency services, Disabled drivers  
Cordon pricing                                                                                                 |
| Edinburgh| To reduce congestion  
To fund projects necessary to achieve the objectives of the LTS and RTS that are not fundable from existing sources  
To distribute the benefits from the charging scheme fairly in respect of people paying the charge  
*(Congestion Relief-Revenue Growth-Equity/Social Inclusion)* | 20%-33% decrease of car traffic  
• Transfer to PT/other modes | Weekdays 7.00-18.00 flat toll, with unlimited entrances, exits and travels                                                                                                  |
| London   | Reduce congestion  
Make radical improvements to bus |                                                                                                                                                                                                                                    |                                                                                                                                                                                                          |
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<th>Goal</th>
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| Manchester | Tackle congestion-Improve PT (Congestion Relief)                      | 37% increase in traffic speed  
Congestion delays decreased 30% during peak hours  
Bus congestion delays decreased 50%  
Bus ridership increased 14%  
Subway ridership increased 1%  
Taxi travel costs fell 20-40% | Cordon pricing-flatt toll for unlimited crossings of one cordon ring, during peak times on weekdays  
Exemptions: emergency vehicles, motorcycles, busses, coaches and registered community transport vehicles, taxis, regular treatment patients of nearby hospitals |
| Milan      | To reduce the environmental impacts of travel  
To improve city comfort and cleanliness  
To support the local economy  
To reduce the health impacts from local transport emissions (Environmental Protection-Liveability-Economic Growth-Health) | Decrease by 56.7% of Euro 0, 1 and 2 vehicles  
Increase by 5.5% of Euro 3, 4 and hybrid/electric vehicles  
Traffic reduced by 14.4% within the Ecopass area and 3.4% outside the zone (These changes can be attributed to 35% route change, 17% of car fleet renewal with less polluting vehicles and 48% of modal shift with 5.7% increase of PT)  
Increase of 6.7% in commercial speeds  
Reduction by 14% of PM10, 11% of NOx, 9% of CO₂, 37% of NH₃ | Ecopass: Daily or multiple passes, depending on the pollution class of the vehicle-optional yearly pass for residents  
Exemptions: mopeds, scooters, motorbikes, vehicles of disabled people |
| Nord-Jaeren| To raise revenue (to co-finance a package for coordinated development of the transport system in the region) (Revenue Growth) | Flat toll, paid 24 hours/day, all year round, charging 1 trip per hour  
Exemptions: buses, emergency vehicles, motorcycles and mopeds, electric operated vehicles, disabled people, tractors and farm vehicles, trips from own house to municipality centre |
| Oslo       | Raise revenue to finance investment in road and PT infrastructure (Revenue Growth) | Flat toll, paid 24 hours/day, all year round, no extra peak surcharge, fees differentiated based on light or heavy vehicles and charging ring  
Exemptions: buses, emergency vehicles, motorcycles and mopeds, electric operated vehicles, disabled people |
| Rome       | The overall goal is to produce a mechanism that encourages modal shift away from Private transport to Public Transport  
Dedicate all revenue to mobility related projects (to recover the environmental externalities rising from traffic pollution and to invest on new PT projects).  
Reduction of congestion  
Lower pollution (Congestion Relief-Revenue Growth-| | |

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<th>Location</th>
<th>Key Objectives</th>
<th>Strategies</th>
<th>Pricing Strategies</th>
<th>Exemptions</th>
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<tbody>
<tr>
<td>Singapore</td>
<td>Relieve congestion (by lowering traffic in the RZ) (Congestion Relief)</td>
<td>Traffic reduced 45% into the RZ Increase in congestion during non-ALS (peak) hours 16% decrease during peak hours - 7% switched to other routes due to cost - Changed departure times - Switched to PT - Carpool - Abandoned trips 17% decrease on peak hour traffic Better speeds</td>
<td>ALS: Daily/monthly license-peak hour pricing (unlimited passes during designated hours) RPS: Linear passage congestion tolls (flat toll) ERP: Variable congestion pricing-Demand sensitive congestion toll-Varying rates based on vehicle size</td>
<td></td>
</tr>
<tr>
<td>Stockholm</td>
<td>Relieve congestion (by curbing vehicle ownership) (Congestion relief)</td>
<td>22% decrease of traffic across cordon 16% decrease of traffic within cordon Congestion delays fell 30%-50% in arterials, less in the cordon Emissions fell 8,5% to 14%, depending on the kind of pollutant PT trips increased by 4,5% across the cordon</td>
<td>Road taxes, Car-park fees, petrol taxes</td>
<td>Cordon pricing-Variable toll depending on the time of day, varied also by emission standards Exemptions: buses, emergency vehicles, electric and hybrid cars, traffic between Lindingo island and rest of country that spends less than 30 min crossing the charging zone</td>
</tr>
<tr>
<td>The Hague</td>
<td>Tackle congestion (Congestion Relief)</td>
<td>A reduction of rush-hours car trips by about 50% was observed. This reduction was obtained mainly by rescheduling trips to earlier or later points in time. A shift to public transport occurred</td>
<td>Reward for drivers that avoid travelling during peak hours</td>
<td></td>
</tr>
<tr>
<td>Trondheim</td>
<td>To raise private sector revenue to feed an urban transport investment package Secondary demand management objective (Revenue Growth-Congestion Relief)</td>
<td>Flat toll depending on time of day (6.00-10.00 or 10.00-18.00), possible discount if prepaid, only one crossing charge per hour Exemptions: disabled drivers, electric cars and public utility vehicles</td>
<td></td>
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</tr>
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</table>
9.2. Maps illustrating the effects of the pricing schemes on the network

Map 1, Most congested highways on peak for zero case
Map 2, v/c ratio in and around Rotterdam on peak

Map 3, v/c ratio in and around Rotterdam off peak
Map 4, v/c ratio in and around Utrecht on peak

Map 5, v/c ratio in and around Utrecht off peak
Map 6, v/c ratios in and around The Hague on peak

Map 7, v/c ratios in and around The Hague off peak
Map 8, v/c ratio in and around Amsterdam on peak

Map 9, v/c ratio in and around Amsterdam off peak
Map 10, Difference in traffic for kilometre charge of 0.03 Euros, on peak

Map 11, Difference in traffic for kilometre charge of 0.06 Euros, on peak
Map 12, Difference in traffic for kilometre charge of 0.09 Euros, on peak

Map 13, Difference in traffic for kilometre charge of 0.12 Euros, on peak
Map 14, Difference in traffic for kilometre charge of 0.03 Euros, off peak

Map 15, Difference in traffic for kilometre charge of 0.06 Euros, off peak
Map 16, Difference in traffic for kilometre charge of 0.09 Euros, off peak

Map 17, Difference in traffic for kilometre charge of 0.12 Euros, off peak
Map 18, v/c ratios for a kilometre charge of 0.03 Euros, on peak

Map 19, v/c ratios for a kilometre charge of 0.06 Euros, on peak
Map 20, v/c ratios for a kilometre charge of 0.09 Euros, on peak

Map 21, v/c ratios for a kilometre charge of 0.12 Euros, on peak
Map 22, v/c ratios for a kilometre charge of 0.06 Euros, off peak

Map 23, v/c ratios for a kilometre charge of 0.09 Euros, off peak
Map 24, v/c ratios for a kilometre charge of 0.12 Euros, off peak
Map 25, v/c ratios for a kilometre charge of 0.03 Euros for Amsterdam, on peak

Map 26, v/c ratios for a kilometre charge of 0.06 Euros for Amsterdam, on peak
Map 27, v/c ratios for a kilometre charge of 0.09 Euros for Amsterdam, on peak

Map 28, v/c ratios for a kilometre charge of 0.12 Euros for Amsterdam, on peak
Map 29, v/c ratios for the city of Amsterdam for a kilometre charge of 0.03, off peak

Map 30, v/c ratios for the city of Amsterdam for a kilometre charge of 0.06, off peak
Map 31, v/c ratios for the city of Amsterdam for a kilometre charge of 0.09, off peak

Map 32, v/c ratios for the city of Amsterdam for a kilometre charge of 0.12, off peak
Map 33, Difference in flows with cordon pricing of 1 Euro taking effect, on peak

Map 34, Difference in flows with cordon pricing of 2 Euros taking effect, on peak
Map 35, Difference in flows with cordon pricing of 3 Euros taking effect, on peak

Map 36, Difference in flows with cordon pricing of 4 Euros taking effect, on peak
Map 37, Difference in flows with cordon pricing of 1 Euro, on peak

Map 38, Difference in flows with cordon pricing of 2 Euros, on peak
Map 39, Difference in flows with cordon pricing of 3 Euros, on peak

Map 40, Difference in flows with cordon pricing of 4 Euros, on peak
Map 41, Difference in flows with cordon pricing of 1 Euros, off peak

Map 42, Difference in flows with cordon pricing of 2 Euros, off peak
Map 43, Difference in flows with cordon pricing of 3 Euros, off peak

Map 44, Difference in flows with cordon pricing of 4 Euros, off peak
Map 45, v/c ratios for the cordon pricing of 1 Euro for Amsterdam, on peak

Map 46, v/c ratios for the cordon pricing of 2 Euro for Amsterdam, on peak
Map 47, v/c ratios for the cordon pricing of 3 Euro for Amsterdam, on peak

Map 48, v/c ratios for the cordon pricing of 4 Euro for Amsterdam, on peak