Effects of road pricing – some suggestions based upon experience from urban areas like Stockholm.

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Abstract.

In this paper, we list the experiences of road congestion regulation using a road price system in Stockholm, Sweden. We add findings of a quantitative regulation system in Oslo, Norway when the road authorities closed tunnels towards the center June 1, 2015. We add findings in Oslo and Stockholm where politicians designed a policy to improve road use organization. We add an analysis by a Danish economist Jens Warming in 1911. He designed a model to regulate exploitation of exhaustible fish resources and showed that regulation policy reduces exploitation and secures the available stock of these resources\(^2\). Warming introduced what he defined as a social revenue correction of private revenue that agents based their market behavior on. Unregulated market behavior with free accessible and exhaustible resources can drain such resources. We define an urban road transport networks that will have similar exhaustible characteristics. Introducing road price changes road users’ behavior, thus such a regulation systems can optimize road use utilization, free urban area for different purposes and solve the problems of the commons. We present Braess’ paradox and discuss a consumer choice dilemma in choosing transportation in morning rush hours.

1. Introduction.

Probably, every day there are less road users compared to available road capacity in any region and at any time of the day in all Nordic countries. In shorter periods, mainly in the urban road transport network the number of road users exceeds available road capacity and it creates congestion. Congestion periods varies in length and in time. However, this chosen action is an individual optimal choice for any road user. For those already commuting along urban road networks this individual optimal choice is harmful. We explain this as a “bathtub effect”; the number of cars entering the network at any entering point exceeds the number of cars leaving at different points along the network. We visualize this as free accessible capacity up front and at the end of the congested network.

Here we will introduce an article Jens Warming presented in 1911 in a Danish journal using a neat model for a brief analysis of how a regulatory regime may function. Since our focus here is regulation of private activities with social consequences, we think Warming’s approach is highly relevant for road price or quantitative regulation. In Denmark around the turn of the century, it was a public debate about free or regulated access to fishing. The discussion focus was on how free access to fishing would utilize accessible resources. One essential question was if and whether unregulated, access could destruct or even devastate existing

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\(^2\) The article was written in Danish and has later been translated into English where the most referred to now is the translation by Peter Andersen and titled “On Rent of Fishing Grounds” in History of Political Economy Vol. 15 (1983). M. Pacheco Coelho describes in “On Rents of Fishing Grounds” Revisited Warming’s career and the legacy of him. See International Journal of Latest Trends in Finance & Economic Sciences No. 2 (2011).
stock. Warming designed a model with potential fish catch volume. In his model, Free accessible fishing led to fish catch level that was beyond maximum revenue. An extra fisherman reduces catch and influences all other fishermen fishing. Thus, Warming added a social element to the private agent's behaviour in a free accessible or unregulated market in his analysis. In Warming's model, an extra fisherman's action varies with what he achieves as an average revenue (in Warming this defined as private revenue). An extra fisherman reduces potential revenues for all other fishermen. Then Warming can model marginal revenue (which then is social revenue) in the free accessible market. Warming introduces revenue regulations and a fee to correct the individual fisherman's action; this fee adjusts individual fisherman's private revenue to the social (marginal) revenue generated by fishing activities.

![Figure 1: Warming's redesigned model for fishing field regulations](image)

Easier catch by more efficient and fewer fishermen optimize revenue maximizing fish volume at field A. Thus, the optimal higher fee at field A adjusts catch and reduces less fishermen. On the other hand, an optimal lower fee at field B excludes more fishermen. We will use this when we explain the outcome with the road price regime in Stockholm. In a paper presented on a Nordic conference in Kristiansand, Norway, we presented a more deepening analysis. For interested persons see this paper (Hauge and Topp [2012]). Probably, an unexpected outcome since a much higher fee excludes much less efficient fishermen. Less efficient fishermen pay a low optimal fee that excludes more. This we use to explain why a low road price introduced by the Stockholm Road Authorities excludes up to 22 % of the road users as Jonas Eliasson shows in a study of the Stockholm case (Eliasson [2014]). We show similar effects in a mirrored Warming's model below. We define this fee as a reflection of an area rent. Thus, an optimal fee maximizes area rent. In a mirrored model, we mirror average and marginal revenue function as an average and marginal cost function. The road price adjusts private car users' private cost to the marginal (defined as social) cost of the others, affected road users commuting in congested urban road network.

We mirror Warming analysis by changing it from a revenue function to a cost function approach. Thus, we get a similar to a model F. R. H. Knight published in an article on the interpretation of a social cost function a decade after Warming, a theoretical knowledge we use when we analyse regulations to curb congestion. Private car user has alternative roads

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3 We presented a paper at The 12th Nordic Conference on History of Economic Thought in 2012 in Kristiansand, Norway titled "Are there signs of influence from Warming in modern Economic thinking?" where we referred to Knight's Some Fallacies in the Interpretation of Social Cost; The Quarterly Journal of Economics, Vol. 39, No. 4 (1924) to show this (Hauge & Topp 2012).
available. This way, the user can change travel behaviour; potential alternatives make market reaction for these road users is clearly more price elastic. Within what is standard microeconomic modelling, fewer, less accessible transport alternatives changes transport use for commuters going to work for instance as a reaction to road price signals. Private car users commuting to work in the morning and going home in the afternoon have fewer options compared to a private car user travelling randomly along the same road. Then, it is possible to observe less elastic demand for daily commuters, information a regulatory board aimed to set an optimal road price level can find utmost useful. Thus, random users probably change travel behaviour easier at any time. As shown in the model below, a low road price level is a strong enough signal for a larger part of the users so they change behaviour. In a mirrored Warming model, a regulatory board can design the optimal fee and reach an aim to adjust the road use in congested periods within such a road price regime. We are able to show the variable effects of car use regulation designing different fees adjusted to variable congestion periods in different urban road networks.

![Diagram](image)

**Figure 2: Cost effects in a congested urban road transport network linking two points.**

With free access to a congested urban road, number of users exceed what we define as the road capacity: therefore, the road becomes congested. Alternative regulations of private car use is among others plate number or passenger number regulations two different policies tested out as a mean to curb congestion. We restrict our analysis to a road price system used in Stockholm and quantitative regulation observed when closing the Smestad tunnel in Oslo.

2. **Empirical findings influencing congested road regulations.**

The Stockholm Road Authorities launched a road price pilot project on January 3, 2006 and later the permanent road price regime in 2007. It is almost 40 years later then Dieter Braess presented a paper on *A traffic Networks* in 1968 in German (Braess [1968]). In addition, in 2000 Sandmo published *The Public Economics of the Environment* in which he presents a Prisoner’s dilemma game theory approach to road transport use. He shows that road price regulation can solve the private car user’s dilemma (Sandmo [2000]). Duranton and Turner presented a paper titled “The fundamental law of road congestion: Evidence from US cities” as an article in The American Economic Review in October 2011. Here the present findings by analyzing new data describing city level traffic in the continental US between 1983 and 2003. This is the way they conclude: "...findings suggest that both road capacity expansions and extensions to public transit are not appropriate policies with which to combat traffic congestion. This leaves congestion pricing as the main candidate tool to curb traffic..."
congestion" (page 2651 Vol. 101, NO. 6, October 2011). We use those three references to stress the probable effects and potential gains of a road price regime in Stockholm. Maybe the road authorities in Stockholm introduced the test project for road pricing in 2006 using the outcome of probably the more known regime: London road price regime from 2003.

The Stockholm case was a three-fold design: Firstly, a test period starting from January 3 and ending on July 31, 2006. Secondly, the city returned to the former free access regime, a referendum held in September 2006 (where a majority of the electorate voted yes), and a third element when the city introduced a permanent regime after August 15, 2007. Before the test period, the city upgraded its public transport service. The city also launched several potential future transport infrastructure investments to reveal bottlenecks. A special element in the Stockholm regime was a referendum: people decided in a referendum whether they would support or reject the road price regime. This referendum is an interesting element that Eliasson underline in a presentation of the test project outcome with a permanent road price system, a presentation you can watch as a TED-presentation available on the following site here: [https://www.ted.com/talks/jonas_eliasson_how_to_solve_traffic_jams?language=en#t-488316](https://www.ted.com/talks/jonas_eliasson_how_to_solve_traffic_jams?language=en#t-488316). The pilot test confronted both The Braess’ paradox of traffic networks as well as Sandmo’s Prisoner’s dilemma giving the city better functioning road system and extra public transport services. Let us present the most relevant findings useful in our paper as the following:

1) A low road price between 10 – 20 SEK depending on the time of the day.
2) What Eliasson calls “a little nudge” is all Stockholm needed to curb congestion.
3) Traffic speed goes up and reduces transportation costs for private car users.
4) Traffic reduction in the test period and the following years has been around 20 %.
5) Those excluded private car users actually have no idea that they are.
6) The support for the charging system went up to 70 % after the system started.
7) A large reduction of travel times up to at least 40 % to more reliable travel times.
8) The need for public transport for extra public service for new users was very low.
9) Shorter travelled distance and less pollution (CO₂-emission down 2 – 3 %).
10) Afterwards, private car user claimed his mind was unchanged since he had not changed his travel patterns.

Using the model Warming presented in its mirrored version can explain such results. Thus, it is not surprising to see traffic reductions like this using the Warming analysis. In our opinion, maybe the most important knowledge is this: Road pricing do not take the private car away from the user. Belief in and need for “buddy for trip” or “travel mate findings” is irrelevant for those excluded are random private car users we cannot recognize in advance. Alternatives like picking private car users entering the congested roads will not work. There are myriads of car users, they are using the road often only once, and they do no return later. Eliasson calls the private car users multifaceted. We add that they are single users; the best way to organize a congested road network is a road price system creating a price signal and leave the decision to any single user in the newly created market. Furthermore, a large public transport service expansion and larger public budget spending, is unnecessary. It will be no need for extra road transport capacity by investing in new roads need not be the answer. The state owned Norwegian Broadcasting Cooperation (NRK) discussed congestion problems in a program April 1, 2014. Let us therefore look into the closing of two out of four tunnels on the road to Oslo centre from northwest E18 known as the Smestad-case.
In the morning June 2, 2015, the Norwegian Road Authorities expected congestion to last for four hours in the rush hours with the reduced tunnel capacity by 50%. Media observed that morning more or less free-floating traffic and no congestion. We observe similar effects using quantity reduction as with road price regulation. A researcher Aud Tønøy at the Institute of Transport Economics TØI together with Professor Petter Naess, The Norwegian University of Life Sciences (NMBU) and Professor Tor Medalen, The Norwegian University of Science and Technology (NTNU) studied the Smestad-case. Aftenposten, a major, nationwide newspaper in Norway, interviewed Tønøy on the closing day where she announces that the tunnel closing will not increase congestion. Below we list Smestad-case study findings Aftenposten presented on Jan 10, 2016. In addition, Tønøy was also the transport research expert NRK used to present congestion causes and effects in a program titled “A life in congestion” on April 1, 2014. Accessible and needed knowledge media needed to recognize and understand congestion and its effects were available over a year ahead of the closing of the Smestad-tunnels. In the next part, we will discuss this.

In 1998, Singapore established an electronic road price system, in Europe London followed up in 2003, and in Norway, the local government in Trondheim introduced the road price system in 2010. Astrid Amundsen, TØI and Joel Franklin, The Royal Institute of Technology (known as KTH) in Stockholm publishes “The road or congestion pricing systems” in 2016 (see Amundsen & Franklin [2016]). The study findings by TØI traffic congestion effects of the quantitative regulations have similar effects as road price systems:

1) Traffic speeded up so the time spent in congestion went down.
2) Reduced travel so travel times were reliable.
3) No additional increase in delays and no expansion of congestion periods.

In February 2016, The Norwegian Road authorities closed 50 % of another tunnel in Oslo from south. Here they offered free parking to reveal congestion, but the effect was similar. In this period, out of 850 parking places at maximum around 50 places were occupied. The private car users find other alternatives so the need for parking the car is very low. This will influence the policies for the road authorities with regulated capacity as well as road price regulations.

In Trondheim in 2008, the road authorities closed down two out of four lanes for private car use and made these two lanes exclusive for public transport services. Both higher commuter speed for people using cars in addition freed road capacity for public services elsewhere. In Trondheim, we see similar findings as we see in Oslo: less congestion with fewer private car users driving faster and using less capacity after closing the two lanes. We describe this as a "bathtub effect": The number of users entering the network exceeds number of users leaving the network and the road network gradually is more congested. Closing lanes reduces number of user in a period to generate the same effects as road price does. In small town Molde on the West Coast of Norway, we see this pattern in the afternoon rush hour with five exits along the congested road between a major industrial site and the airport area. People who need to catch afternoon flights choose an alternative road. When they enter at the fourth exit, it is almost no congestion on the road after this exit. The effect is similar to water filling up a bathtub. Private car commuters entering the main road towards the airport area fill up the road and more enter than leave the first three exits: private car users entering is less then car users leaving the road. From the fourth exit, the traffic speeds up and it eases the flight
passengers ability to catch the next flight. They need less time to commute along a longer distance. Using the studies of both Trondheim and Oslo, we may claim that both quantitative and road price functions as draining the congested road lanes in the urban networks. In Molde, it is only a single lane road. Even though, the documentary on NRK mentions Molde as a special case with a low number of inhabitants and a very simple road network. We conclude so far this way: Single private car user act according to standard behavior we model in microeconomics. His choice is rational; he reduces road use in congested periods when he has to pay a road price at the preferred road. The most price elastic private car drivers leave the road that is no longer free accessible. Now, we are able to focus on the effects of and how congestion influences travel time and travel behavior.

3. Major findings influencing use of traffic regulations and capacity building.

Now, we are able to list some of our findings by summing up both the Stockholm-case and the Smestad-case. The essential information is that road price and the quantitative regulation will reorganize urban road use. In congested periods, a road price signals to a user that if he chooses to commute this extra traffic causes social effects the road authorities will influence. They demand that private car users must pay if he enters the network in congested periods. It establishes at least a virtual or even a real market for road use, this signal changes some user's behaviour so they drop out and reduce the number of commuters.

Within a road price regime the road price adjusts private user cost to social cost. Similar to Warming we define this as a land or area rent. A private car user no longer gets free access to road use. Using Duranton and Turner, there is little need for extra public transport services with road pricing. If we link their findings to the effects of the road price introduction in 2006 and 2007 in Stockholm, the economic effects of building extra free accessible road capacity is supporting the physical effects Braess showed in his 1968-article. Extra road capacity will add more traffic and slow down traffic speed.

However, the revenue generated by a road price system increases funding of a municipality's public services. Among other spending, extra revenues may even fund road investments and operation of public funded transport services. However, most important, the road price system reduces the need for road investments. Within an Alonso, land rent bid model, this changes distribution of land. It allows us to reshape urban space (see Narvæz, Penn and Griffiths [2013]). Less private car use in congested periods frees urban central area, in Barcelona where available area expanded the no private car area.

Another information in Eliasson's study report is that we do not know who are dropping out, it is impossible to find out why they no longer commutes in the congested periods. We cannot even map them in advance; we cannot observe them if entering congested roads. We cannot even point out in what periods they are present. Such commuters we do not know who they are and if they are commuting more than once and later never return.

On average, every fifth excluded commuter if he or she has to pay a road price. Still, these excluded commuters do not change transport mean, but go on driving a private car. If they drive on this particular road in another period, is beyond information. Probably, many will still drive on an urban road. In Oslo, neither excluded commuter driving a private car will not
crowd out other private car users in housing areas. They need not find a mate, a buddy, or even not a place to park and ride on public service.

In Stockholm and in Trondheim, expanded public transport services ahead of a road price regime, handled more and more of the commuters. We conclude this way: Road price gives no extra signal for commuters to change to public transport services. To change or influence a commuter's choice, the municipality must improve public services. The commuters both in Trondheim and in Oslo are more satisfied with these services. Latest number registered in the two urban areas indicates that more than 50% now commute by public transport to and from the centre on a daily basis. Thus, we think the solutions chosen in Oslo and Trondheim will influence and probably increase the public transport service use. Following Narvaez, Penn and Griffiths this has socioeconomic and spatial effects that can help urban authorities to reshape street configuration (Narvaez, Penn and Griffiths [2013]).

In addition, less congestion lowers travel time and frees road capacity for both private car users and operation of public transport services. Public services need fewer units, operation cost is lower and this requires less time to operate services. Public transport service provider can use extra capacity and saved cost to expand the services. In a road price regime, extra revenue collected can create opportunities for public sector to offer more or to improve public transport services. We think a good way is to increase frequency and reshape the service design. Furthermore, a mix of express, hub-to-hub and ordinary all stops services will lower the operation time even more. On average, service stop time is shorter; speed goes up and shortens service operation time. This reduces the social cost not only for the private car user, but also for the public service commuters.

A road price introduction reduces what we call a bathtub effect; a physical effect caused by a commuter up front driving slower than those behind. A road price frees inaccessible capacity ahead of the slower driving commuter, and speed up all private car commuters behind. The road price introduction in Stockholm also indicates that the commuter up front may have a lower time value than those behind. The losses for all other commuters gradually grow when the queue behind is growing. Those queuing up in a growing number behind have a higher time value. A road price system reduces social cost so loss for individual user now drops. A road price corrects private transport cost on that road in that mode at that time is. Faster speed for the remaining commuters reduces the social cost and improve the road transport organization.

More and more urban areas in Norway are evaluating urban centre activities where some of the suggested alternatives are already tested. Exclusive bicycle lanes, closed mingle areas for pedestrians (can include bicycles as well), closed shopping areas and daytime parking restrictions. Now, Barcelona's "superblocks" shape are probably the most discussed urban area solution in literature right now. The solution leaves the area free of private cars. Private car users need to increase travel time by a few minutes to cross a longer distance like 3 000 extra yards. With no private car use, it frees area for other purposes for local inhabitants, so such areas are less polluted, less noisy and get a "green outlook". Look up the presentation to see a complete closed area with no way to challenge, overrun or obstruct the solutions: it can be studied via: http://www.businessinsider.com/barcelona-superblocks-ban-cars-2016-10?r=US&IR=T&IR=T. The extra travel cost for private car users are small, the benefit of using the area for those living there probably outweigh at least the extra travel costs.
Using a mirrored Warming model, we can discuss the road price regime within a common goods access regulation framework. Modelling a fee introduction let us create what can be a social optimized market behavior. A regulatory board influences private car commuter's road use and can achieve optimal values for a society now using more of its available resources. A road price = area rent collects extra revenue so within a Warming model we can find a better if not optimal outcome like Eliasson shows in Stockholm. Regulations using road price or quantitative measures have been tried out so we can observe effects like Duranton and Turner, Eliasson and the Smestad-case studies indicate that the need for extra road or public transport services is more or less absent. For many reasons road price regime can optimize road use. The system can fund different designed, extra public transport services capacity. A free accessible, social optimal urban road network could create a social optimal system for both passenger and land transport use that will benefit all of its users.


In this paper, we define an urban road network as a human made physical construction governed by physical laws. A transport literature road network structures have links and at some spots and in a shorter period capacity is limited and create bottlenecks. Such transport bottlenecks reduces the traffic speed. This reduces traffic volume across a given distance in shorter periods so the network drain fewer private car users. Private car users cannot drive at an optimal or even at an accepted speed. Volume per unit of time is lower and the road traffic is congested.

One way to visualize useful for analysis of a large urban road network is to define this as a bathtub (or a very large bottle). In congested periods, reduced speed reduces volume flow so the network drains less private car users. In a short run, either the physical capacity is given or it is costly to add extra capacity. If urban road authorities want to challenge congestion problems, two major measures can improve traffic flow; reduce number of users or add links. Both in London, Stockholm and Trondheim road price changed the road use organization and increased travel speed for those car users still using urban roads. The commuters' travel time was shorter when at least every fifth user changed behavior and left, this increased road capacity. In Stockholm and Trondheim, road authorities introduced new links with extra public transport services in advance. Updated statistics indicate a significant commuting shift towards public service in Trondheim and Oslo by improving the public services. Underground services add capacity in London, Stockholm and Oslo. Investing in more public services can establish more links and eliminate existing bottlenecks cheaper than building more unregulated road capacity.

Anyhow, extra public transport services are more flexible and less costly than expanding the road network. Experiences from Trondheim and Oslo indicate that private car users change their mind even though they need not pay road price. Eliasson et al’s study of the Stockholm-case do not find these users so they cannot map users excluded by the road price system. In Eliasson's words, the potential private car user is not aware of the road price or that she or he has changed behavior. The support of the road price after the popular referendum seems to have grown with the benefits private car users gained. People living inside the Stockholm ring want to expand the road price system. Probably, it is a similar effect for people in Oslo: they hand few problems to handle daily commuting with more than 20 % road capacity reduction in the maintenance period.

We use the fundamental law of road congestion to conclude that added, extra capacity will not solve congestion problems. Instead, road price frees capacity; in Trondheim, the road
authorities used the free or extra capacity to introduce more exclusive public transport service lanes. In our bathtub analysis, the effect is two-folded: more traffic flow reduces bottlenecks and it creates extra links so traffic speeds up and volume flow grows. Let us suggest an expanded differentiated public service as a mix of express, hub-to-hub and ordinary services in congested periods.

At the same time, it is not necessary to expand urban public transport services. Private car users find alternative ways to commute in the congested period. In our opinion, findings in the Stockholm-case using road price regulation and the Smestad-case in Oslo adding a quantity reduction period shows similar findings as in Duranton and Turner's study of major US urban areas. All these cases have a similar outcome; less congestion that reduces marginal cost, this reduces the social cost of any commuter in the congested periods. Lower travel cost benefits every user since it reduces the user’s generalized travel time cost. A song by Peter Gabriel inspired us to present this article. We think the actual song visualizes this: someone literally looking down on an empty street from what is gradual taller buildings in an urban center. Road authorities uses costly infrastructure investments to occupy urban areas where a private car user gets free access so she or he can park in a center where more area is free accessible. A road price regime frees such areas for other purposes like mingling local inhabitants in Barcelona or cyclists in Copenhagen. The system collects revenues that can fund other public services. Road price introduction will not demand extra public service capacity. Public sector can offer many other alternative services. Anyhow, the road price reduces losses for all other road users if the price excludes a marginal user. Within an Alonso land rent bid auction the value of urban area may be growing by redistributing an urban center's area.

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