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The Zebra Crossing Game
– a game theoretic model to explain counter-rule interaction between cars and cyclists

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ABSTRACT

In Norway, bicyclists are allowed to cycle on the pavements and cyclists and pedestrians share dedicated and common tracks for walking and cycling. Crossings between such tracks and the roadway are normally marked with zebra crossings. When cyclists cross the road either from a pavement or from a cycle (and walking) track, they are supposed to yield to crossing traffic on the road. However, when pedestrians cross over the zebra crossings the cars must yield according to the law.

In such crossing situations, the cyclists have three options. They can (a) yield to the cars, (b) cycle over the zebra crossing (and risk a collision), or (c) jump off their bicycle and walk over the zebra crossing, and thus force the car drivers to yield. The drivers have two choices, either to drive (x) or to yield (y). According to the rules the solution is a/x or c/y. However, it can be shown that neither of these solutions are in perfect equilibrium, and the game theoretic solution to the game is in fact b/y, i.e. that the cyclists cycle over the zebra crossing and the cars yield, contrary to what the traffic rule prescribes. Thus, according to game theoretic reasoning one should expect the normal solution in road traffic would be that drivers yield to cyclists in zebra crossings.

In order to test the hypothesis, empirical observations of crossing behaviour was conducted in two crossing situations in Oslo, Norway, one crossing situation where cyclists approached from the pavement and another situation where cyclists came from a crossing cycle and walking track. The results reveal that actual crossing behaviour follows the expectation from the game theoretic model and not the traffic rules.

The results show that game theoretic modelling can be a valuable tool to understand road user interaction [1, 2].

Keywords: cyclists, cars, interaction, game theory.

1 INTRODUCTION

Infrastructure and rules for cycling differ greatly between countries. Some countries like The Netherlands and Denmark have built dedicated separated cycle lanes and tracks for cyclists, whereas in other countries cyclists and pedestrians share the areas separated from the motorized traffic. In Norway, the normal layout is a combined cycle/pedestrian lane, separated from the motorized traffic. Mopeds and motorcycles are not allowed to enter such cycle/pedestrian lanes. In addition, in Norway cyclists are allowed to cycle on the pavements.

Because cyclists are allowed and expected to share the same areas as pedestrians, areas for crossing the roads like zebra crossings are also shared between cyclists and pedestrians. However, the rules concerning the right of way at such crossings differ between cyclists and pedestrians. Pedestrians have the right of way at zebra crossings and cars must yield. For cyclists this is not the case; if they cycle over the zebra crossing they must yield to crossing cars. However, if they jump off the bike and walk, they are considered as pedestrians and the cars must yield.

The give-way rules for cyclists were changed in 1998. Before that, when cyclists came from the pavement and crossed the street in an intersection, the right-hand rule was applied. If cyclists came from the right-hand side, cars had to yield regardless of whether the cyclist entered the intersection from the pavement or the street. In addition, vehicles turning had to yield to those going straight, also to cyclists coming from a pavement and going straight over the intersection. Accordingly, in many cases cars had to yield to cyclists in zebra crossings before the law was changed. After 1st of May, 1998 the give-way rules became stricter for cyclists. From now on, the cyclists were obliged to give way to cars when crossing the street from the pavement irrespective of coming from the right or left and irrespective of crossing in a zebra crossing or not. In zebra crossings, the only way to obtain the right of way would from now on be to jump off the bicycle and walk over the zebra crossing.

2. THE USE OF GAME THEORY TO STUDY ROAD USER INTERACTION

Game theory is a tool to model and analyse social situations where people interact, and where all actors involved are influenced by the outcome of interaction. Furthermore, when the interaction is modelled as a game, it is assumed that every actor influences the result, but that no actor can single-handily determine what outcome that will be realized. Game theory is thus concerned with decisions under uncertainty where the surroundings are not parametric, but strategic; they consist of other actors who also influence the probability of different consequences. The essence of game theory is therefore, that each actor must take account of the fact that other actors will influence the outcome, and thus he must decide what to do on the basis of predictions of what other relevant actors will do. Furthermore, he must realize that the other actors will make their decisions based on similar considerations. This "symmetric" decision problem is essential in game theory.

Traditionally, game theoretic models are based on very strict assumptions of rationality and information. It is assumed that all players know the "rules of the game", i.e. the number of actors in the game, the possible actions or strategies each actor may choose, and even how different actors value different outcomes. In addition, all actors are assumed to be rational in the sense that they have the cognitive (and mathematical) skills necessary to calculate an optimal strategy which may be to choose alternative a with probability p, alternative b with probability q, and alternative c with probability $1-(p+q)$. Such assumptions of rationality and information are unreasonable when the focus is on decisions in road traffic. When road users interact in traffic, decisions will normally have to be made quickly, and thus there will be important limitations on the actors' cognitive capacities.

During the last 40 years much work has been done on repeated games, and on games where the actors play sequentially, i.e. on games with a dynamic element [3-6]. In such models, the assumptions of information and rationality are often less strict, and the possibility that actors learn what actions, or strategies that are most successful by experience in the game, is considered. Such models can both be models where the same actors play some game sequentially or models where some constituent game or static game is played for a repeated number of times by the same actors (super-games), or models where the same game is played repeatedly but where the actors involved change over time (compound games). Such dynamic game theoretic models, where the assumptions of information and rationality are not so strict, are the game theoretic models with the greatest potential to study road user interaction.

Road traffic interaction is an obvious arena where such models ought to be relevant. Still, game theory has not been used much in road traffic research, except for e.g. Bjørnskau [1], Prentice [7] and Bjørnskau & Elvik [8]. Elvik [2] presents a few more studies that use game theory to model road user behaviour. Nevertheless, examples from road traffic are very often used in the game theoretic literature [6, 9, 10, 11]. The game theoretic model that is most often used to describe road user interaction in the research literature is "Leader" [12, 1], also named as "Cross-roads" by Sugden [6]. The "Zebra Crossing Game" presented below is a variant of the classic Leader game.

3 THE "ZEBRA CROSSING GAME"

The Zebra Crossing Game model presented in figure 1 is a game theoretic model where the actors are supposed to move sequentially and where both parties know the other parties previous moves in the game. Thus, the model is presented in so-called extensive form in order to capture this dynamic aspect of the game. In the game only ordinal values are assumed, i.e. that the actors rank the different outcomes from 6 to 1, where 6 represents the best outcome and 1 represents the worst outcome. Thus, it is not possible to compare the utilities for drivers and cyclists in the game and the valuation of the utility derived from the different outcomes may vary between different actors. However, it is assumed that the ordinal preferences capture how both drivers and cyclists normally rank the different outcomes.

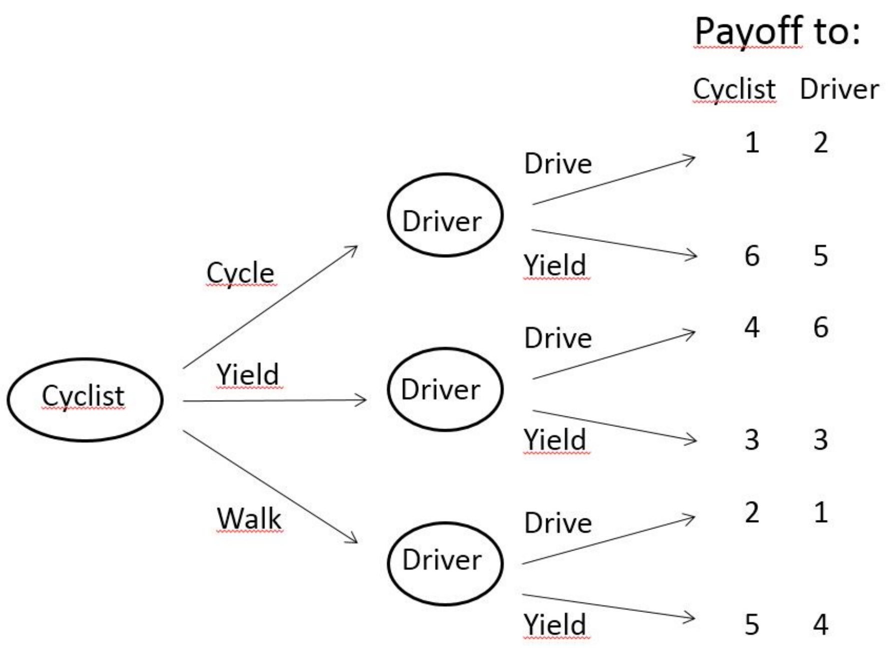

Figure 1. The "Zebra crossing game", in extensive form with ordinal valuations of outcomes: 6 > 5 > 4 > 3 > 2 > 1.

In the Zebra crossing game depicted in figure 1, the cyclist has three options; a) she can cycle over the zebra crossing, b) she can yield to crossing cars or c) she can jump off the bicycle and walk over the zebra crossing. The car driver has two options either to drive or to yield. In the model, it is assumed that both parties prefer solutions where they can continue to move to solutions where they have to wait. It is also assumed that collisions represent the most negative solutions for both actors.

The best outcome for the cyclist (6) is when she can continue cycling over the zebra crossing and the crossing car yields. The second best outcome (5) for the cyclist is when she jumps off and walks over the crossing and the car yields. This is considered a better outcome than when the cyclist yields to the driver (4). A worse outcome results when both yield (3). This is bad for both actors because then no solution is reached and they need to negotiate again in order to settle the game. The worst outcome for the cyclist is when she cycles over the crossing and the car does not yield resulting in a collision (1). To the cyclist this is worse than if she walks over the crossing and the car drives (2). In the latter situation, the driver has broken the traffic rules and therefore it can be expected that she will receive better compensation than if she had cycled, since in that case she was the one breaking the traffic law.

The best outcome to the driver is when he can continue unhindered i.e. the cyclist yields (6). The second best outcome to the car driver (5) is that he yields and the cyclists cycle over the zebra crossing. This is considered better for the driver than if the cyclist jumps off the bike and walks over the zebra crossing (4) since it is less time consuming also for the driver. The outcome that both yield is considered a bad outcome (3) since this outcome does not give a solution to the game. The worst outcome for the driver is when he drives and hits a person walking over the zebra crossing (1). In that case, he will be at fault, he will receive a harsh penalty and lose his driver's licence. If the driver drives and the cyclists cycles over the zebra crossing, the resulting outcome is also bad (2), but not quite as bad because in that case the cyclists has broken the traffic law and the driver will not be penalized (as much).

In this game we assume perfect information; i.e. that both the driver and the cyclist know the other's preferences over the different outcomes and they can observe the other's move and know where in the decision tree they are. Thus, the cyclist knows that the worst outcome for car driver is to hit her when she walks over the zebra crossing.

The standard solutions in game theory are those of Nash equilibria. A Nash equilibrium is a combination of strategies that are such that no actor has any incentive to act otherwise given the other actors choice. In this game, there are two Nash equilibria: Cycle/Yield (6,5) and Yield/Drive (4,6). The outcome Walk/Yield (5,4) is not a Nash equilibrium; given that the driver yields it is better for the cyclist to cycle than to jump off an walk.

According to the traffic rules there are two solutions here, either the cyclist yields and the driver drives, or the cyclist walks and the driver yields. However, as mentioned, the solution Walk/Yield (5,4) is not a Nash equilibrium and accordingly not a stable solution according to game theoretic reasoning. The solution Yield/Drive (4,6) is a Nash equilibrium, but not a perfect equilibrium [3], and thus not a stable solution. The only stable solution in the game is Cycle/Yield (6,5) which is also a perfect equilibrium. In order to identify this as a perfect equilibrium solution to the game we can adopt so-called backward induction, i.e. we reason backwards from the different outcomes to what strategies the player's would adopt in order to realize the best solution to himself.

Thus, the cyclist may reason as follows; according to the rules, I must either yield or jump off and walk over the zebra crossing. If I yield, the driver will drive, and the outcome will be yield/drive (4,6). This is a solution according to the rules (and Nash equilibrium), but the cyclist can achieve a better outcome by choosing to jump off and walk over the zebra crossing instead. The cyclist has the first move in the game and she knows that the car driver will yield in that case and thus the outcome will be walk/yield (5,4). This is also a solution according to the traffic rules, but not an equilibrium solution. Given this outcome, the cyclist may reason as follows: given that the driver yields, it is better both for me and for the driver that I cycle over the zebra crossing instead of walking. The solution cycle/yield (6,5) is preferred also by the car driver to the solution walk/yield (5,4). Accordingly, based on game theoretic reasoning we would expect the solution to be that cyclists cycle over the zebra crossings while cars yield, contrary to what the traffic rules prescribe.

The following hypothesis were put forward by Bjørnskau in 2001, based on the then rather recent changes in the give-way rules and the type of game-theoretic reasoning presented above: "In a few years the normal practice is probably that drivers yield to cyclists at zebra crossings" [13].

4 METHOD

In order to test what solutions in fact are realised in this game, registrations of real life encounters were carried out in three different crossings in Oslo, Norway, at three different periods in time, in 2007, 2012 and 2014. Not all locations were covered every year. The crossings and registration times were:

A. Nordbergveien/Kaj Munks vei – Rolf Wickstrøms vei ("Tåsen") in April 2007 and May-June 2012
B. Sognsveien/Ring 3 ("Ullevål") in April 2007, May-June 2012 and September 2014
C. Zebra crossing in Maridalsveien ("M.veien") in May 2007.

In A and C there is a zebra crossing where cyclists (and pedestrians) cross from the pavement; in B there is a combined walk/cycling path crossing Sognsveien marked with zebra stripes.

Data was collected during peak-hours, i.e. in the morning (08:00-09:00) and in the afternoon (16:00-17:00) by manual registrations. Registration periods varied from 20 minutes to 1 hour. Only cases where one or both of the interacting cyclists and car drivers had to yield were registered. If cyclists approached as a group or in a queue, only the first cyclist was registered. The reason for this was that if a driver had stopped for one cyclist he would normally also remain standstill for an immediately following cyclist. Thus, only if the distance to the following cyclist was 5 meters or more, a new case was registered. In addition, we omitted cases if a pedestrian crossed the zebra crossing at the same time as a cyclist. We registered both who yielded and whether cyclists jumped off and walked. In the latter case, car drivers always yield.

5 RESULTS

The results are presented in table 1 and figure 2.

In all periods and at all crossings there is a clear pattern that car drivers tend to yield to cyclists. This varies from 84% of all situations in the morning traffic at Tåsen in 2012, to 57% of the situations in M.veien in the morning traffic in 2007. The pattern in M.veien differs from the other situations with a marked greater proportion of cyclists jumping off their bicycles and walking over the zebra crossing. In M.veien one in four cyclists chose to do so in 2007. In the other situations, less than ten per cent of cyclists choose this option, except at Tåsen in 2007 with 13 per cent. A chi-square test reveals that the distribution in M.veien is different from the aggregated distributions at the other crossings ($\chi^2=24.2$, $p<0.01$).

In general, the pattern is quite consistent over time. It looks as if there is a slight tendency that car drivers yield somewhat more often in 2012 than in 2007 at Tåsen, but not at Ullevål. A chi-square test reveals that the differences between 2007 and 2012 at Tåsen is not statistically significant, regardless of whether we look at the differences during morning traffic or morning and afternoon traffic combined.

Table 1. Results of observations of yielding behaviour in three different zebra crossings in Oslo during morning and afternoon traffic in different years. Per cent.

	M.veien	Tåsen				Ullevål				
	Morning	Morning		Afternoon		Morning			Afternoon	
	2007	2007	2012	2007	2012	2007	2012	2014	2007	2012
Car yields	56.6	74.1	83.9	72.7	79.3	77.8	75.9	76.9	77.8	79.8
Cyclist yields	18.9	19.0	7.1	14.3	15.2	18.1	17.2	17.9	18.1	14.7
Cyclist walks - car yields	24.5	6.9	8.9	13.0	5.4	4.2	6.9	5.1	6.9	5.5
N	53	58	56	77	92	72	54	39	87	272

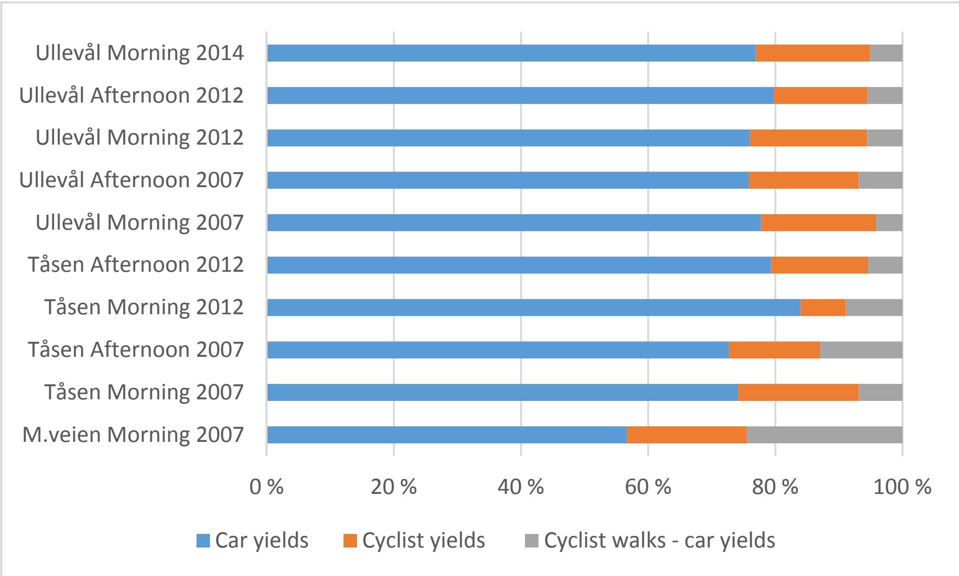

Figure 2. Results of observations of yielding behaviour in three different zebra crossings in Oslo during morning and afternoon traffic in different years. Per cent.

6 DISCUSSION

The general picture is quite clear; car drivers give way to cyclists at zebra crossings contrary to what the traffic rules prescribe. This seems to be a very widespread and stable solution in two of the three zebra crossings investigated. In the third, at M.veien, there are much more cyclist that jump off and cross as pedestrians. That M.veien differs from the two other locations is not surprising. M.veien is located in an urban, gentrified area in Oslo with lots of young people moving around on skateboards, bicycles, as pedestrians etc. The cyclists here are typically city cyclists without much equipment, often on typical city cycles going at low speeds, and easy to jump off. The crossing behaviour here is much more "chaotic" than at the two other locations that both are on the cyclist "highway" following Ring 3 around the city, dominated by "transport" cyclists with helmets and other cyclist equipment (jackets, shoes etc.).

The Zebra Crossing Game is a type of Leader-game where the first mover has a clear advantage. Here it is assumed that the cyclist has the first move, which is decisive for the solution in this game. If modelled with car driver as the first mover, the outcome will be that he drives and the cyclists yields. As we have seen, this solution is also experienced in real-life interactions albeit much more seldom than the solution we have identified. In other traffic cultures, such similar situations may have very different solutions due to different traffic cultures and thus different preferences in the game. An important point in Norway is that drivers must yield to pedestrians at zebra crossings and are strictly penalized in the case of a collision with a pedestrian. Accordingly, a very important driving force in this game is the ability for cyclists to switch to becoming pedestrians and thus forcing car drivers to yield. Their ability to use this role transformation as a credible threat is of course dependent on the speed and distances of the actors involved when a cyclist and a car approach a zebra crossing. Sometimes the car driver manages to reach the crossing just in time to gain a first mover advantage whereby he can safely pass without risking hitting the cyclist. He may even speed up to obtain such an advantage. However, this happens very seldom as indicated by the results of the registrations.

The normal course of action in the Zebra Crossing Game is that both the cyclist and the driver reduce speed, and that the cyclist crosses before the car. Thus, they are aware of each other and they interact actively. In many such cases, the cyclist's speed reduction may be interpreted to the driver as a kind of threat that if the driver does not signal that he will give way, the cyclist may jump off the cycle, "forcing" the driver to yield. The fact that a stable proportion of 5-10 per cent of the cyclist choose to jump off and walk, may contribute to keeping drivers constantly aware of this option, and thus aware of the logic of the game.

Thus, quite often in these interactions, the cyclists and the drivers communicate and negotiate and very often car drivers signal clearly to cyclists that they will give way to the cyclist, and thus avoid the extra delay involved when a cyclist jumps off and acts as a pedestrian. Over time, it seems that the logic of the Zebra Crossing Game has given rise to a norm or informal rule that drivers should yield to cyclists at Zebra Crossings, and that that car drivers behave towards cyclists much in the same fashion as they do towards pedestrians.

7 CONCLUSION

We have used a simple game theoretic model to analyse the interaction between cyclists and car drivers at zebra crossings in Norway. Here the formal traffic rule prescribes that cyclist should yield to cars. However, by analysing the interaction in game theoretic terms it becomes clear that the solution that car drivers yield to cyclists is the most likely solution of this interaction in Norway. Registrations at three zebra crossings in different years reveal that the game theoretic solution in fact is the by far most frequent solution in real life.

Given the fact that the actual behaviour in these situations are contrary to what the traffic rule prescribes, one could argue that either should the rules be changed or they should be better enforced. However, the Norwegian road authorities have so far not suggested to change the rules nor to increase the enforcement. The reason is that the current pattern of interaction ensures that crossings are conducted at low speeds with road users being very much aware of each other, and generally producing quite safe crossings. If cyclists were given the right of way, one could easily imagine that they would cross at much higher speeds making it difficult for drivers to spot them in time. On the other hand, if the current rules were to be more strictly enforced it would probably lead to huge protests because the current interaction pattern seems to work quite well. Furthermore, according to the assumptions of the zebra crossing game, to enforce the traffic rules would give a solution neither the cyclists nor the car drivers prefer.

The game theoretic analysis presented reveals that game theory can be a fruitful tool to analyse road user interaction.

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