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MANAGING TRAFFIC BEHAVIOUR. A THEORETICAL EXAMINATION OF AGGRESSIVE DRIVING THROUGH A MARKOVIAN MODEL

Driving safety is a major concern all around the world of both the concerned authorities and the general public. In the context in which aggressive driving behaviour is generally considered to be a major cause of traffic accidents, the study of such a problem can help policy-makers in their endeavour to design better programs that aim at reducing aggressive driving behaviour. The purpose of the present paper is to analyse the above-mentioned problem by considering short- and medium-term alternative measures in terms of social cost. The optimal combination of short- and medium-term solutions will be shown to depend on the drivers' level of aggressiveness, which, naturally, also depends on the gap between the existent infrastructure and the volume of motorized traffic. Special attention is given to the impact of civic campaigns on the level of aggressiveness.

Keywords: *traffic, aggressive, driving, cooperative, competitive, behaviour, model*

1. Introduction and theoretical framework

Driving is a complex, cognitive-behavioural task that many individuals perform every day [15]. According to the World Health Organization [19], road accident-related injuries are major causes of deaths worldwide. In the United States alone, for example, according to Centers for Disease Control and Prevention [6], motor vehicle crashes are of great concern, given that they represent one of the main causes of death (as the number 1 killer) for people aged from 1 to 44 years. In this context, driving safety is a major concern all around the world of both the concerned authorities and the general public. The subject literature contains a number of studies that have looked more closely into

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what actually predicts driving safety, among which we can mention the drivers' steering performance, the use of turn signals, and horn honking. Generally, the existent studies in the field can be classified under three broad categories: studies based on field observations, studies based on surveys, and studies using driving simulators [3].

For example, some authors [5, 10, 13, 16] show that excessive steering activity and high steering activity are intimately linked to the increased at-fault safety errors. Kiefer and Hankey [11] and Zhang et al. [21] identify that not using the turn signals before lane changes may cause lane changes crashes. Turner, Layton, and Simons [17] suggest that aggressive driving behaviours are associated with the excessive use of the horn, while McGarva, Ramsey, and Shear [12] find that male drivers generally express their frustrations while driving through excessive horn honking, which creates a contagion effect in other drivers, leading to unsafe driving conditions. Finally, Dula and Geller [8] associate excessive horn honking with hazardous driving. Shinar and Compton [14] pay attention, however, to the cultural aspect of such behaviours, suggesting that these can actually be controlled by cultural norms. A more recent study by Yuan et al. [20] shows that high-risk drivers drive much faster and exhibit larger offsets of the steering wheel than low-risk drivers in events without incidents and that high-risk drivers use turn signals and horns less frequently than low-risk drivers.

In the present paper, we are interested in modelling the aggressive behaviour of drivers. It should be noted that the operational definition which we assign to the concept of aggressive driving is characterized by dangerous behaviours without the intent to cause harm to oneself or others, but which pose a heightened risk of crashes. In the literature, the above definition is sometimes associated with risky driving rather than with aggressive driving. Some authors make a sharp distinction between the terms (for example, Dula and Ballard [7] assign the element of intent – that is, deliberately endangering others – to aggressive driving behaviour). We consider that while such distinction might be of relevance at a more theoretical level, for all practical purposes of the present paper, this differentiation is void, as long as we state our position. Furthermore, our position is supported by existent literature, such as the study by Vanlaar et al. [18], who assess that while behaviours such as street racing and speeding up through a traffic light might be perceived as aggressive by the general public, they may not actually be intended to cause harm to others.

As Abou-Zeid, Kaysi, and Al-Naghi [3, p. 1] assess, *aggressive driving is typically stimulated by impatience, frustration or anger and manifests itself through unsafe driving behaviour such as running red lights, traffic weaving, or tailgating*. This situation is compounded in major cities in emerging countries that experience a high rate of economic growth. The shortfall in the urban traffic infrastructure is aggravated by the rapid increase in motorized units of transportation, especially under circumstances of lacking or deficient service of the public transportation system.

Aggressive driving behaviour is generally considered to be a major cause of traffic accidents (see, e.g., [1]) or of motor vehicle crashes [4]. Speeding is the number one cause of traffic fatalities and accidents [9], also affecting the severity of crashes [2]. In this context, the study of such problems can help policy-makers in their endeavour to design better programs that aim at reducing aggressive driving behaviour.

The purpose of the present paper is to analyse the above-mentioned problem by considering short- and medium-term alternative measures in terms of social cost. The short-term measures encompass more policies, fines, and civic campaigns, among others; while the medium-term measures are considered in extreme situations: the appeal to focalized traffic infrastructure investment to attenuate bottleneck situations, such as auxiliary roads, two-level ways, express roads, improvement in traffic signalling, and so on. No consideration of major investment in the traffic infrastructure to face the real problem will be considered. The optimal combination of short- and medium-term solutions will be shown to depend on the level of drivers' aggressiveness, which, naturally, also depends on the gap between the existent infrastructure and the volume of motorized traffic. Special attention will be paid to the impact of civic campaigns on the level of aggressiveness. To the best of our knowledge, no such or similar study has been undertaken in this regard.

The remainder of the paper is organized as follows: the following section describes the setting underpinning traffic behaviour along with the assumptions and the driving behaviours considered. Further, technical details which describe the Markovian model are provided. Then, the analysis section follows, with a subsequent section which discusses the obtained results. Insights and conclusions are provided in the last section.

2. The setting

Before proceeding with a characterization of the setting, we offer the following definitions and descriptions of the parameters considered:

State S_1 – coopetition state. This is a state characterized by the alternating behaviour of the drivers between cooperative and competitive behaviour. At the aggregate level, traffic behaviour is complicated, but with restricted aggressiveness. There is a deficit in traffic infrastructure relative to the volume of motorized vehicles but, in general, driving behaviour is oriented towards the good performance of the traffic, and not only towards the particular interests of each driver. This general situation is affected by the competitive behaviour of some drivers in certain situations in which competitive behaviour is characterized by aggressiveness in pursuing personal benefits in terms of time delays. If uncontrolled, this particular aggressive behaviour could propagate (contagion) among drivers, and eventually produce a transition to a chaotic state, S_2.

State S_2 – competitive state. This state is characterized by a generalized competitive behaviour among drivers which behave aggressively on the roads. Drivers focus mainly on their own interests, respecting neither other drivers nor traffic regulations. Under this behaviour, the problems created by the gap between transit infrastructure and the volume of motorized vehicles compounds, producing a chaotic situation. This chaotic situation feeds back into the drivers' behaviour, elevating aggressiveness and further deteriorating the situation. Time delays materialize in an increased number of accidents, stress, and pollution, among others.

Social costs. The costs for society are generated by time delays, stress, pollution, accidents, injuries, and deaths, among others. These social costs depend on what state the system is in. What matters is the relative costs between both states. We have the freedom to define the units to measure these costs, and we take the social costs related to state S_1 as the unit of measurement, specifying a cost of one unit of social cost for each period the system is in S_1. Relative to these unitary costs, the social cost per period for remaining in state S_2 is specified as $H \geq 1$.

Policy actions. Two types of policy actions are considered by the authorities: short-term measures (SMs) and medium-term measures (MMs). These measures are decided by the authorities. SMs are easy and fast to implement, and represent current expenditures; examples of this type of measures are civic campaigns to promote good driving and civic behaviour, fines, traffic control signals, and so on. These measures are taken by the authorities in both states S_1 and S_2. The emphasis on SMs is measured by the investment that these measures absorb, which is represented by α and measured also relative to the unitary social cost of being in state S_1. The range considered for α is between 0 and 1.

MMs, on the other hand, involve fixed investments in infrastructure for specific situations or geographic areas. Examples are investments in new systems of signalling, two-level roads, auxiliary roads, and so on. These measures are taken only in state S_2. The emphasis on these MMs is measured by the investment that these measures absorb, which is represented by δ and measured also relative to the unitary social cost of being in state S_1. The range considered for δ is between 0 and 1.

No long-term measures (LMs) are considered. LMs involve high fixed investments that completely change the transportation system of the city; not only is the investment high, but also the time schedule to implement them is long-term. LMs resolve the gap between infrastructure and the volume of motorized vehicles. Examples in this sense are road networks, subways, railroad systems, general computerized systems, and so on. LMs would transform driving behaviour into cooperative behaviour.

The setting is characterized by:

- A major city in an emerging economy experiences a sustained high rate of economic growth. The economic growth reverberates in the high rate of growth of motorized units of transportation and the volume of traffic in general, which cannot be accompanied by the growth of the traffic infrastructure.

• The situation generates an aggressive behaviour in drivers who overpass traffic regulations and exhibit a chaotic traffic behaviour. Social costs are high and they can be judged from the perspective of the longer time needed for transportation, pollution, stress, and accidents, among others.

• Two states are considered. In one state, drivers behave by alternating between a cooperative driving and an aggressive or competitive driving. We denominate this state as the coopetition state – or a mixture of cooperative and competitive behaviours. For this state only, the following short-term measures are in use: policies, fines, civic campaigns, and so on. The level of use of such measures, both in terms of intensity and coverage, is under the control of the authorities, but it has a cost (cost here refers to the expenses incurred for the implementation of the civic campaigns, fines, and policies, among others). From that state, the situation could make a transition to a second state, completely chaotic, in which most of the drivers behave aggressively. This transition from the former state is generated in part by a contagion effect, resulting from the higher benefits perceived and which are derived from a competitive behaviour (we define higher benefits as individual incentives or advantages that can be obtained by not following the rules as opposed to following the rules, mainly, less driving time). This state is referred to as the competition state. In this state, social costs are much higher than in the former state. The situation is in crisis and forces authorities to take some medium-term measures besides the short-term ones. The medium-term measures consist in focalizing the infrastructure investment to attenuate specific bottleneck traffic situations.

• No state of full cooperation is considered; only coopetition and competition states are considered.

• No major long-term solution for the situation is considered; only combinations of short- and medium-term measures are taken into account. The ruling out of a major long-term solution also rules out the existence of a cooperation state. It is assumed that a long-term solution will eliminate the gap between the infrastructure and the volume of traffic and foster cooperation among the drivers (i.e., the civic campaign will be effective).

3. The model

To analyse the problem, the Markovian model shown in Fig. 1 is further considered. In the figure, S_1 corresponds to the coopetition state and S_2 corresponds to the competition state. As previously mentioned, being in any of the two states implies costs for society. In terms of costs, we have the freedom to specify their units; let us consider the cost of one unit for staying in S_1 and a cost of H units by being in a state S_2.

Transition state probability from S_1 to S_2. The transition from S_1 to S_2 depends naturally both on the level of aggressiveness of drivers and on the contagion effect among the drivers; this is represented by a transition probability of β. But this natural probability is affected by the level of short-term measures taken by the authorities to attenuate the aggressive behaviour of the drivers, which is represented by α which is positive and less or equal to one. A greater α means a greater effect on the attenuation of aggressiveness. Thus, we postulate equation:

$$p_{12} = \beta(1-\alpha) \tag{1}$$

where α and β are positives and less or equal to one, and receive the following denominations: β – level of aggressiveness, α – level of enforcement. This transition implies no cost, and following the convention, we will call it a null reward. Thus, the reward of the transition from S_1 to S_2 will be zero, i.e., $r_{12} = 0$.

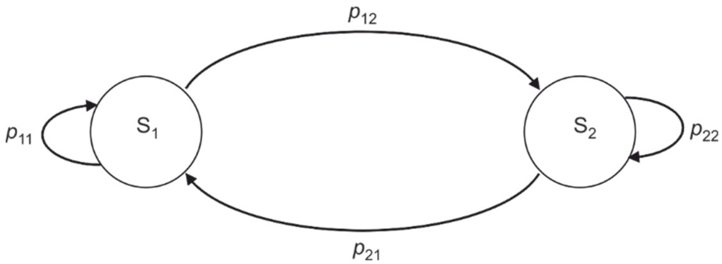

Fig. 1. Transition diagram

Transition state probability from S_1 to S_1. By default, we have the transition state probability from S_1 to itself defined by the equation:

$$p_{11} = 1-\beta(1-\alpha) \tag{2}$$

This transition will imply a social cost of 1 and an additional cost generated by the level of enforcement, which depends on α; hence, we have $r_{11} = 1 + \alpha$, $0 < \alpha < 1$.

Transition state probability from S_2 to S_1. In state S_2, the competition state, there is a crisis situation: the chaos is such that additional measures of enforcement have to be taken. These measures are directed at attenuating the major focalized traffic bottlenecks at peak time, which implies traffic infrastructure investment, as well as possible changes in signalling systems and others. We represent this level of investment as δ, which is a level of investment made each time the system remains in the state S_2. The longer the system remains in the state S_2, the greater the number of bottlenecks that appear and that require further investment in attenuating them. We consider that the level of investment δ is less or equal to the cost of being in S_1, which is one unit, each time the system is in S_1. A higher δ will imply a higher probability of leaving S_2 and a transition to S_1, thus we consider a natural probability of δ of transitioning from S_2 to S_1, where δ is the level of investment per period while remaining in S_2. We consider that the probability of transitioning from S_2 to S_1 depends on the natural probability δ affected by the level of enforcement, and also negatively affected by the level of aggressiveness. Specifically, we consider the following equation:

$$p_{21} = \delta(1-\beta)(\alpha) \tag{3}$$

Furthermore, we consider no cost for the transition from S_2 to S_1; thus, the reward for this transition will be null, i.e., $r_{21} = 0$.

Transition state probability from S_2 to S_2: By default, we have the transition state probability from S_2 to itself defined by the equation:

$$p_{22} = 1-\delta(1-\beta)(\alpha) \tag{4}$$

The transition from S_2 to S_2 generates a social cost of H units and costs related to investment in infrastructure and enforcement; hence, $r_{22} = H + \alpha + \delta,\ H > 1$.

4. Analysis

Based on the above, we have the following transition state probability matrix **T** and reward matrix **R**:

$$\mathbf{T} = \begin{bmatrix} p_{11} & p_{12} \\ p_{21} & p_{22} \end{bmatrix} = \begin{bmatrix} 1-\beta(1-\alpha) & \beta(1-\alpha) \\ \delta(1-\beta)(\alpha) & 1-\delta(1-\beta)(\alpha) \end{bmatrix} \tag{5}$$

$$\mathbf{R} = \begin{bmatrix} r_{11} & r_{12} \\ r_{21} & r_{22} \end{bmatrix} = \begin{bmatrix} 1+\alpha & 0 \\ 0 & H+\alpha+\delta \end{bmatrix} \tag{6}$$

with the following restrictions:

$$0 < \beta < 1, \quad 0 \le \alpha \le 1, \quad 0 \le \delta \le 1, \quad 1 < H$$

We are only concerned with the asymptotic behaviour of the system, and given that the system is completely ergodic, the limiting state probability will not depend on the initial state. The limiting state probability will be defined by the left eigenvector of the transition matrix **T**, corresponding to its largest eigenvalue, i.e., $\lambda = 1$:

$$\boldsymbol{\pi} = \begin{bmatrix} \pi_1 & \pi_2 \end{bmatrix} \tag{7}$$

where:

$$\pi_1 = \frac{\delta(1-\beta)(\alpha)}{\delta(1-\beta)(\alpha) + \beta(1-\alpha)} \tag{8}$$

$$\pi_2 = \frac{\beta(1-\alpha)}{\delta(1-\beta)(\alpha) + \beta(1-\alpha)} \tag{9}$$

The expected cost of the next transition is given by equation (10):

$$\mathbf{q} = \begin{bmatrix} q_1 \\ q_2 \end{bmatrix} \tag{10}$$

where:

$$q_1 = p_{11}r_{11} + p_{12}r_{12} \tag{11}$$

$$q_2 = p_{21}r_{21} + p_{22}r_{22} \tag{12}$$

We are especially interested in the gain of the system defined by equation (13):

$$g = \pi q = \pi_1 q_1 + \pi_2 q_2 \tag{13}$$

which is the expected cost per transition under asymptotic behaviour.

Our main interest lies in analysing the relationship between the level of aggressiveness and the gain of the system, under conditions of optimal selection of the level of α and δ, and taking into account the relative social cost between S_1 and S_2: $H/1 = H$. We are also concerned with the effect of β on π_1 and π_2, always under optimal decision for α and δ, and the relationship between β and the optimal values of α and δ.

Numerical estimations were obtained for the limiting state probabilities, the gain, and the ratio of short-term and medium-term investment, as a function of the level of aggressiveness. These estimations were found for the following scenarios:

H – 1, 1.2, 1.4, 1.6, 1.8, 2.0,

β – 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9,

α – 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9,

δ – 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9.

From these estimations, values of σ and δ that minimized the gain were considered. Specifically, for a given H, and for each β, the combinations of α and δ that produce the minimum g were determined. These optimal values were named as g^*, α^* and δ_i^*, and for the limiting state probabilities: π_1^* and π_2^*. Thus:

$$g^* = g(H, \beta, \alpha^*, \delta^*) \tag{14}$$

$$\pi_1^* = \pi_1(H, \beta, \alpha^*, \delta^*) \tag{15}$$

$$\pi_2^* = \pi_2(H, \beta, \alpha^*, \delta^*) \tag{16}$$

5. Results

Let us consider the following denominations. As stated before, investments and costs are relative to our unit of measurement, which is the unitary social cost related to state S_1; in this context, the social cost H corresponding to state S_2 will be referred to as relative social cost $H = H/1$, or the relative social cost of state S_2 in relation to the social cost of state S_1. On the other hand, we will denominate the par (α, δ) as investment policy and the par (α^*, δ^*) as optimal investment policy.

Figure 2 shows the relationship between the level of investment and the level of aggressiveness, for different levels of relative social cost, H. The situations corresponding to low levels of social cost, $H = 1$ or $H = 1.2$, are uninteresting. As the figure shows, under these scenarios, there is practically no management activity due to the fact that there is not much difference between the two states, S_1 and S_2. In general, the levels of short- and medium-term investments are at a minimum and similar in magnitude, independent of the level of aggressiveness. In these situations, as can be seen in Fig. 3, S_2 is a quasi-trapping state, since the low levels of α and δ make the transition probability p_{21} to be almost zero. For these low levels of social costs, the limiting probability of the chaotic state is almost 1 and for S_1 is almost 0. Figure 4 shows that for these low levels of social costs, the gain is low and independent of the level of aggressiveness for the optimal investment policy: (α^*, δ^*).

Let us consider situations with greater relative costs, H greater or equal to 1.4. As it can be appreciated, for these situations there is room for management in accordance with the level of aggressiveness; nevertheless, this room is finite, as beyond some level of aggressiveness, the investment policy becomes ineffective.

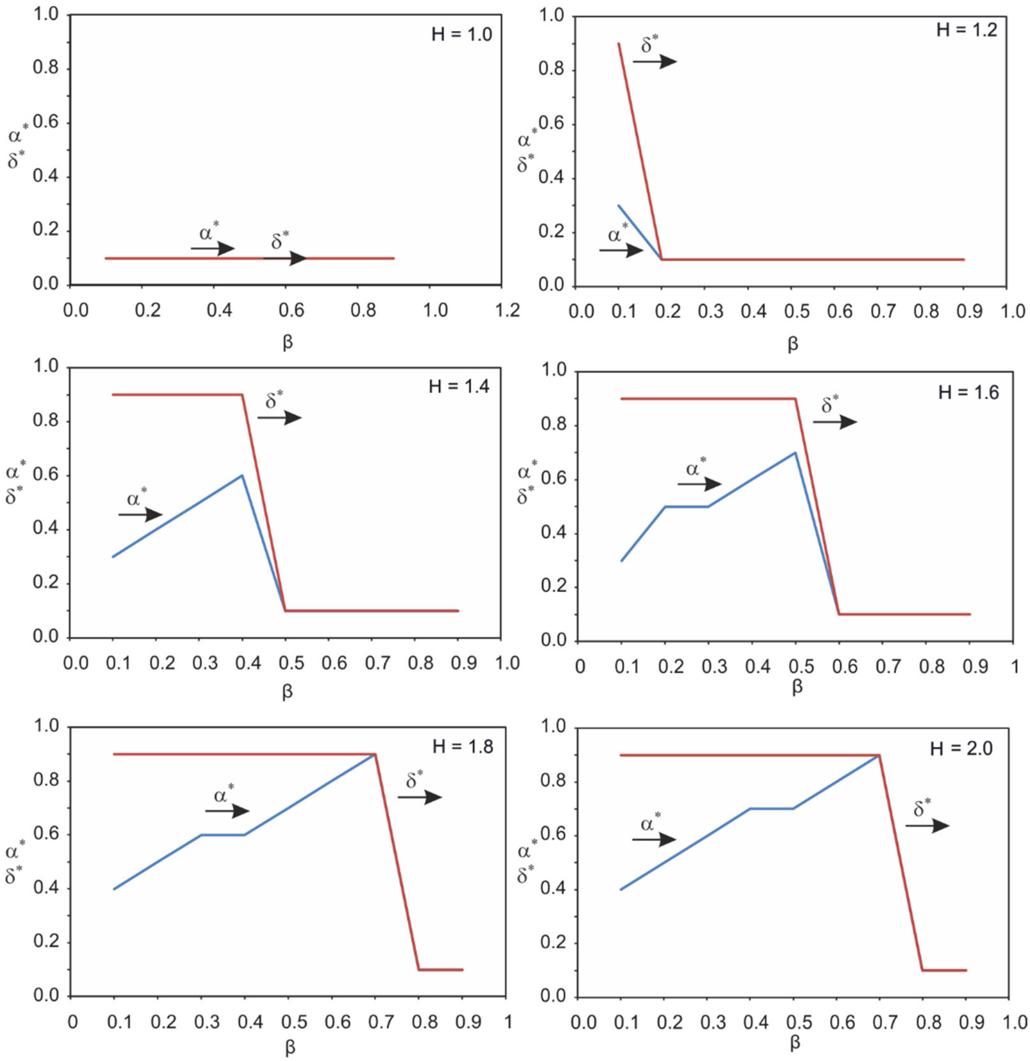

Fig. 2. Optimal investment policy

Under these situations, the figures will show similar patterns in the behaviour of the system. This behaviour is defined by two levels of aggressiveness, a critical level β_c and a saturation level β_s. These levels of aggressiveness, β_c and β_s, will depend on the level of the relative social cost. For levels of aggressiveness below the critical level, i.e., the active management region (AMR), the optimal short-term investment α^* is increasing, and the optimal medium-term investment δ^* is constant at a value close to its higher possible level; the limiting state probability for S_1, π_1^*, is slowly decreasing with the level of aggressiveness β, and the limiting state probability for state S_2, π_2^*, is increasing; within this region, the optimal gain g^* is increasing with the level of aggressiveness.

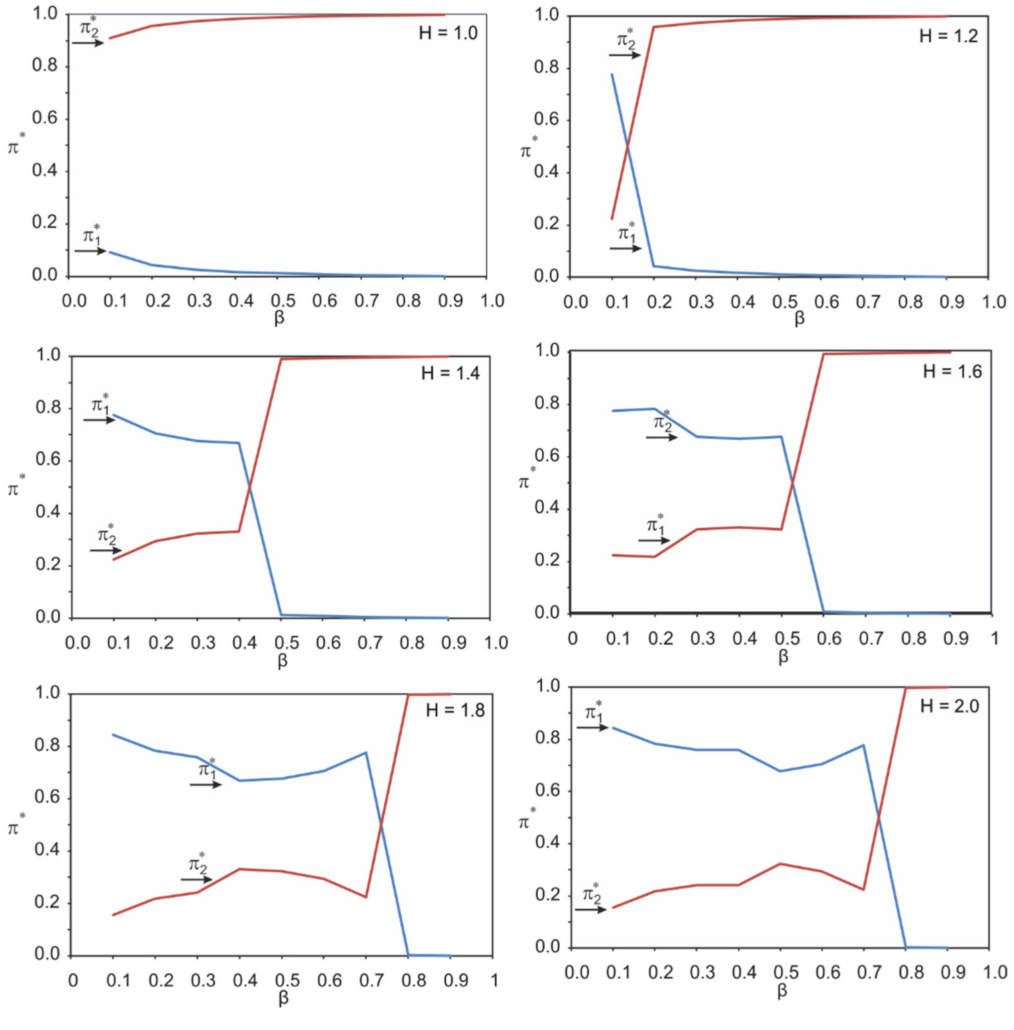

Fig. 3. The limiting state probabilities under optimal investment policy

At the critical level of aggressiveness β_c, the optimal short-term investment α^* reaches its maximum possible level. This maximum level for values of H equal to 1.4 and 1.6 is lower than δ^*, and equal to δ^* for values of H equal to 1.8 and 2.0. The optimal medium-term investment δ^* is on a constant level without a change in the AMR region.

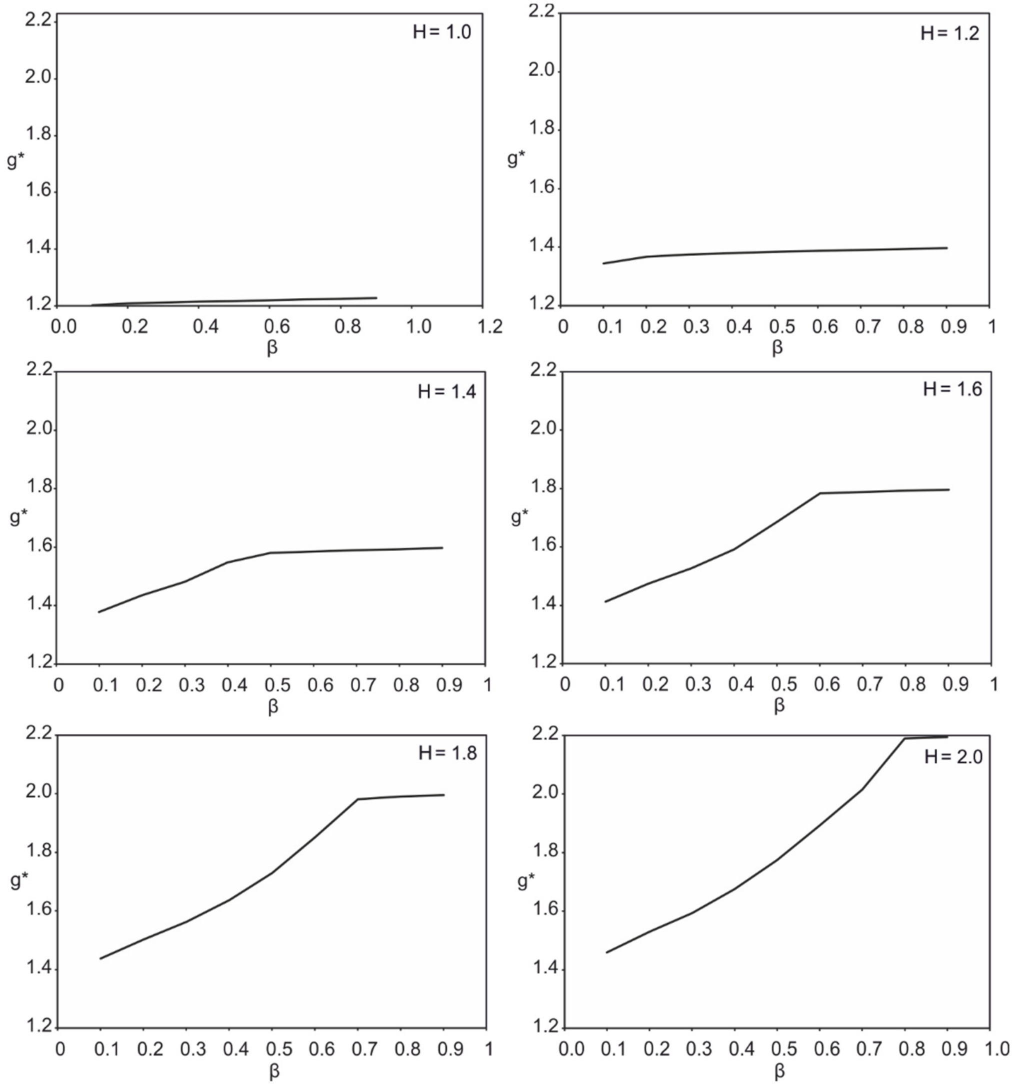

Fig. 4. The gain under optimal investment policy

From the critical level β_c to the saturation level β_s, i.e., the damage control region (DCR), both the optimal short-term and optimal medium-term investments experiment a sharp reduction, until reaching the saturation level of aggressiveness, β_s. The DCR is a short interval, along which both optimal levels of investment drop drastically and the limiting state probability for state S_1 drastically decreases to zero, while the corresponding limiting state probability for S_2 steeply converges to one. Within the DCR, the gain increases with the level of aggressiveness. At the saturation level of aggressiveness β_s, the optimal policy of investment is no investment; the limiting state probability for state S_2 is one, a trapping state, and for state S_1 is null; the gain is basically determined by the relative social cost. For a level of aggressiveness that is higher than the saturation level β_s, i.e., the saturation region (SR), there is no room for management, the optimal investment policy is no investment, the system is always in a chaotic state, and the gain is fixed at a level that is basically determined by the relative social cost.

Let us explain the above in more detail. For this purpose, let us consider one specific case, i.e., the case for the relative social cost of $H = 1.6$, taking into account that all cases exhibit the same pattern of behaviour. Figure 2 shows that in the AMR, the management is actively trying to control the transition to the chaotic state S_2, because of the high relative cost of this state. For this purpose, the optimal short-term investment α^* is increasing with the level of aggressiveness, trying to retain the system in the state S_1; also, the optimal medium-term investment δ^* is close to its maximum level to maximize the probability of leaving the state S_2. As a consequence of this strategy, as can be seen in Fig. 3, the optimal limiting state probability for state S_1, π_1^*, is much higher than the optimal limiting state probability for state S_2, π_2^*, nevertheless, this gap is slowly decreasing as the level of aggressiveness increases, and the optimal gain is increasing, which can be appreciated in Fig. 4. For the level of critical aggressiveness, the optimal level of the short-term investment achieves a maximum level, which is, however, inferior to what could actually be achieved; while the optimal medium-term investment remains at a high level, close to its maximum.

For a level of aggressiveness in the DCR for which β is between its critical level and its saturation level, the management loses power and is oriented to controlling the damages. The aggressiveness is high enough to make it difficult to attenuate the transition to the chaotic state, and the optimal investment policy mainly represents additional costs that negatively affect the gain. As a consequence of this, as can be seen in Fig. 2, the optimal investment policies experiment sharp reductions for increasing levels of aggressiveness, until both types of optimal level achieve their similar minimum levels in the saturation level of aggressiveness.

In the SR, there is no room for management, the level of aggressiveness is high enough to retain the system mainly in the chaotic state, and the investment will only negatively affect the gain, without any benefit. In this region, the optimal investment, both short- and medium-term oriented, is at its minimum, the state S_2 has become a trapping state, and the gain is defined mainly by the relative social costs. In the presented figures, it is to be noticed the influence of the relative social costs on the definitions of critical and saturation levels of aggressiveness, and therefore, on the three regions of AMR, DCR, and SR. The higher the level of the relative social costs, the higher the critical and saturation levels of aggressiveness. Also, it is to be observed that the peak of the short-term investment depends on the relative social costs; in this context, the higher the relative cost, the higher the peak.

6. Conclusions

In the context in which, generally, aggressive driving behaviour is considered to be one of the main causes of traffic accidents, the purpose of the present paper was to analyse the problem of aggressive driving behaviour by considering short- and medium-term investment measures in terms of the social cost that these entail.

From a methodological point of view, we employ a Markovian model to analyse the driving behaviour, in which the transition probabilities are defined by the level of aggressiveness of the drivers (alternation between a coopetitive state and a chaotic state), coupled with the contagion effect among the drivers; and the short- and medium-term investment measures. It is shown that the optimal combination of short- and medium-term solutions depends on the drivers' level of aggressiveness, which, naturally, also depends on the gap between the existent infrastructure and the volume of motorized traffic.

The main conclusion of the paper concerns the situations in which the relative social costs are high enough to make a significant difference between the two states. When the relative social costs are not high enough, both states are almost indistinguishable, and thus, it does not matter in which state the system is. As a consequence, the investment, either short- or medium-term oriented, does not make sense; the chaotic state S_2, which is very similar to the state S_1 of coopetition, is almost a trapping state, the gain does not depend on the level of aggressiveness and is at a relatively low level.

For relative social costs of some magnitude, there is room for management when the aggressiveness has not reached a critical level; beyond the critical level, there is a small region characterized by a control damage management. For higher levels of aggressiveness, the system reaches a saturation region, in which investment does not make sense, practically transforming the chaotic state into a trapping state.

For the figures considered, the damage control region is so small that we have almost a type of "big bang" solution. In the AMR, there is active management trying to retain the system in S_1 and, if it were in S_2, active management trying to determine the system to leave the state as soon as possible. The short-term investment is increasing with the level of aggressiveness and the medium-term investment is at its maximum; the gain is increasing with the level of aggressiveness, and the limiting state probabilities show higher values for the state S_1. The contention is such that the gap between the two limiting probabilities decreases at a very low pace with the level of aggressiveness. If the level of aggressiveness increases beyond its critical level, the system passes very rapidly into its saturation region, where there is no room for management whatsoever. Finally, the sizes of the regions AMC, DCR, and SR depend on the relative social costs.

From a managerial point of view, thus, our findings suggest that driving behaviour management is not an easy task: it cannot be based solely on short- and medium-term investment measures, but it also requires active management of the level of aggressiveness of the drivers. The results, although theoretically-oriented, may prove to be important to the concerned policy-makers, for quantifying the aggressive driving behaviour, setting guidelines for the management of driving behaviour in the country, and for setting appropriate short- and medium-term investment measures in accordance with the respective sector, among others. In short, we hope that the present paper can serve as a stepping stone for further in-depth exploration of the problem of aggressive driving behaviour, which can help policy-makers in their endeavour to design better programs that aim at reducing aggressive driving behaviour.

In terms of avenues for future research, it would be interesting to extend the present research with a study that assesses the robustness of the results found by means of supporting the proposed conceptual framework with real-time data under various scenarios (cross-country and multi-country).

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References

[1] AAA Foundation for Traffic Safety, *Aggressive driving: Research update*, Washington, DC, 2009. Retrieved 13th February 2017 from https://safety.fhwa.dot.gov/speedmgt/ref_mats/fhwasa1304/resources2/38%20-%20Aggressive%20Driving%202009%20Research%20Update.pdf

[2] AARTS L., VAN SCHAGEN I., *Driving speed and the risk of road crashes: a review*, Accident Anal Prev, 2006, 38 (2), 215–224.

[3] ABOU-ZEID M., KAYSI I., AL-NAGHI H., *Measuring aggressive driving behaviour using a driving simulator: an exploratory study*, Article submitted to the 3rd International Conference on Road Safety and Simulation, 14–16 September 2011, Indianapolis, USA, 2011.

[4] BLOWS S., AMERATUNGA S., IVERS R.Q., LO S.K., NORTON R., *Risky driving habits and motor vehicle driver injury*, Accident Anal. Prev., 2005, 37 (4), 619–624.

[5] DONMEZ B., BOYLE L.N., LEE J.D., *Safety implications of providing real-time feedback to distracted drivers*, Accident Anal. Prev., 2007, 39 (3), 581–590.

[6] Centers for Disease Control and Prevention, *10 Leading Causes of Death, United States, 2014*. Retrieved 8th January 2017 from https://webappa.cdc.gov/sasweb/ncipc/leadcause.html

[7] DULA C.S., BALLARD M.E., *Development and evaluation of a measure of dangerous, aggressive, negative emotional, and risk driving*, J. Appl. Soc. Psychol., 2003, 33 (2), 263–282.

[8] DULA C.S., GELLER E.S., *Risky, aggressive, or emotional driving: addressing the need for consistent communication in research*, J. Safety Res., 2003, 34 (5), 559–566.

[9] ELVIK R., *Speed limits, enforcement, and health consequences*, Annu. Rev. Publ. Health, 2012, 33, 225–238.

[10] ENGSTRÖM J., JOHANSSON E., ÖSTLUND J., *Effects of visual and cognitive load in real and simulated motorway driving*, Transport Res. F-Traf., 2005, 8 (2), 97–120.

[11] KIEFER R.J., HANKEY J.M., *Lane change behaviour with a side blind zone alert system*, Accident Anal. Prev., 2008, 40 (2), 683–690.
[12] MCGARVA A.R., RAMSEY M., SHEAR S.A., *Effects of driver cell-phone use on driver aggression*, J. Soc. Psychol., 2006, 146 (2), 133–146.
[13] MUELLER A.S., TRICK L.M., *Driving in fog: the effects of driving experience and visibility on speed compensation and hazard avoidance*, Accident Anal. Prev., 2012, 48, 472–479.
[14] SHINAR D., COMPTON R., *Aggressive driving: an observational study of driver, vehicle, and situational variables*, Accident Anal. Prev., 2004, 36 (3), 429–437.
[15] SUHR K.A., DULA C.S., *The dangers of rumination on the road: Predictors of risky driving*, Accident Anal. Prev., 2017, 99, 153–160.
[16] THOMPSON K.R., JOHNSON A.M., EMERSON J.L., DAWSON J.D., BOER E.R., RIZZO M., *Distracted driving in elderly and middle-aged drivers*, Accident Anal. Prev., 2012, 45, 711–717.
[17] TURNER C.W., LAYTON J.F., SIMONS L.S., *Naturalistic studies of aggressive behaviour: aggressive stimuli, victim visibility, and horn honking*, J. Pers. Soc. Psychol., 1975, 31 (6), 1098–1107.
[18] VANLAAR W., SIMPSON H., MAYHEW D., ROBERTSON R.D., *Aggressive driving: A survey of attitudes, opinions and behaviours*, J. Safety Res., 2008, 39 (4), 375–381.
[19] World Health Organization, *Global status report on road safety 2013: Supporting a decade of action*, Geneva, Switzerland, 2013. Retrieved 8th January 2017 from https://www.who.int/violence_injury_prevention/road_safety_status/2013/en/
[20] YUAN Y., DU F., QU W., ZHAO W., ZHANG K., *Identifying risky drivers with simulated driving*, Traffic Inj. Prev., 2016, 17 (1), 44–50.
[21] ZHANG W., HUANG Y.-H., ROETTING M., WANG Y., WEI H., *Driver's views and behaviours about safety in China – what do they NOT know about driving?*, Accident Anal. Prev., 2006, 38 (1), 22–27.

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