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Abstract

In July 2003 a new Road Code was approved by the Italian parliament. Among many reforms whose validity is not questioned here, the new law states that on three-lane motorways the right lane should not be reserved anymore to slow vehicles alone. As in two-lane roads, all vehicles must now drive on the right lane, as long as it is not occupied by other vehicles. The model developed in this paper casts doubts on the validity of such a change, suggesting that the old rule generally performs better, in terms of number of accidents, average speed and motorway capacity, than the new one. This conclusion is shown to be extremely robust to refinements of the main assumptions concerning driving attitudes and the stochastic arrival of accidents.

Introduction

<<The paramount feature of Italian highway driving is 'il sorpasso'. The word means "to pass with an automobile" and "to surpass or excel." By the way, it is not where you arrive that counts, but whom you pass on the way. The procedure is to floor your accelerator and leave it there until you come upon something you can pass. If 'il sorpasso' is not immediately possible, settle in its wake at a distance of six or eight inches and blow your horn until such time as you can pass. Passing becomes possible, in the Italian theory, whenever there is not actually a car to your immediate left>>.

(http://www.geocities.com/Heartland/Plains/6271/italy003.html)

It is possibly to change such a bad perception of Italian traffic that a new Road Code was approved, in July 2003, by the Italian Parliament. Among other major changes, such as the introduction of a driving license points system, the new Code abolishes the so-called "shame lane", i.e. the reservation of the right lane on three-lane motorways for slow vehicles only. With the new law, everybody should keep the right lane, as long as it is free of other vehicles, as in all two-lane roads. According to the experts of the Transport Ministry, this change should bring down the number of slow downs, since "normally nobody drives on the right lane, and thus Italian motorways are used less than it would be possible". Driving on the slow lane seems to be a shame: the new Code goal is to eliminate the shame from it. The minister, Mr. Lunardi, is also convinced that the reform should have a positive effect on the number of accidents, since "one of the causes of the accidents is that there are slow vehicles on the middle lane".

Sounds reasonable. Unfortunately, it is not true. Simulating two 3-lane motorways, one governed by the old rule ("If you're slow, keep on the right lane and move on the middle lane only in order to pass a slower vehicle in front of you; if you're not slow, keep on the middle lane and move on the left lane only in order to pass a slower vehicle in front of you") and the other by the new one ("Always keep on the further right lane available; move left only in order to pass a slower vehicle in front of you") brings evidence that the opposite is actually the case. The two rules are roughly equivalent with low traffic, but as soon as the inflow of vehicles - and in particular of slow vehicles

- increases, the old rule performs better both in terms of number of accidents and in terms of motorway capacity. When average speed is considered, the results show that with the new rule it is generally lower; moreover, even when traffic conditions are such that the average speed with the two rules is approximately equivalent, the new rule brings more variance, i.e. the number of slow-downs actually increases.

Finally, these findings remain generally true also when the simulation allows for occasional right pass (which is obviously strictly forbidden with both rules). The new rule, by imposing to all vehicles to drive always on the further right lane available leaves literally less room to the temptation of a right pass. However, although the performances of the two rules get closer as we rise the probability of a driver choosing to right pass a slower vehicle in front of him when no left pass is possible, the old rule generally remains better. The results are also robust to other changes in driving attitude.

The paper is structured as follows. Section 1 reviews the existing literature on the topic, with a particular regard to the economic issues involved. Section 2 describes the simulation set-up. Section 3 explains in more details the results. Section 4, 5 and 6 investigate relaxations of the assumptions (namely, the possibility of right pass, the possibility of front crashing in addition to lateral crashing, and the introduction of endogenous distraction probabilities), in order to reproduce more realistic driving patterns. Section 7 concludes.

1. The literature

Traffic problems are analysed from various perspectives. Economists are mainly interested in the external effects involved, such as congestion, while traffic engineers are more interested in issues like the stability of traffic flows. The economic analysis of congestion (a forthcoming survey is Lindsey and Verhoef, 2000) is based on a standard demand and supply framework. However, the standard Pigou-Knight analysis (Pigou, 1920; Knight, 1924) suggests that expanding supply (road capacity) as a remedy to congestion is not only ineffective, but often counterproductive. The reason is that the

amount of traffic is governed by what is regarded as a tolerable level of congestion: if the capacity of the road network is increased, whether by road construction or traffic management measurements, its utilisation will increase until the same conditions obtain. Congestion charges should therefore be the optimal policy.

The Pigou-Knight model of traffic congestion refers to the stationary state behaviour of a population of homogeneous drivers using the same road. Traffic density determines traffic speed by means of an aggregate relationship (the speed-flow curve), which in turns determines transportation time and thus travelling costs. The cost function is taken as a primitive concept. Recent developments (see Rouwendal et al., 2002) consider heterogeneous individual drivers behaving in accordance with the speed choice theory. This theory states that a driver chooses his speed by trading off the benefits of a higher speed (reduced travel time) against the cost of (higher accident risk). The accident risk is related to traffic speed and density.

A different approach is taken by bottleneck models, building on the seminal work of Vickrey (1969), which analyse the behaviour of drivers in queues (see Arnott et al., 1990 for a survey). One central question in this literature is whether the flow of cars through the bottleneck is less than the maximum possible flow (Verhoef, 2002). Bottleneck models are in general based on the car following theory. The intuitive idea that forms the basis of car following theory is that drivers react to the behaviour of the vehicle immediately in front of them so as to avoid accidents. Car following theory (Gabbard, 1991) was elaborated mainly by traffic engineers, which were interested in phenomena such as shock waves. Thus, the idea has not been elaborated by means of models in which costs and benefits associated with a particular speed choice are traded-off against each other leading to a decision to accelerate or decelerate, as an economist would be inclined to do. Instead, it was meant for descriptive purposes, in order to model actual driver behaviour. A trend is now under way to bridge the gap between the two literatures, and provide normative foundations to the car-following theory.

On the other hand, engineers are less troubled by purely behaviouristic models, and have been more concerned with the inclusion of other realistic features of driving attitudes, in order to build reliable models of traffic flows. Thus, lane changing and gap acceptance models have been added to car-following models, following the seminal Gipps models (Gipps, 1981 and 1986). However, realistic descriptions of vehicle's behaviour have proved difficult to integrate in analytical models, which moreover can generally provide solutions only for stationary (i.e. equilibrium) conditions. On the contrary, micro-simulations have proved to be both powerful and versatile.

The relationship between simulation and highly idealized analytical models is of the kind described by Roth and Peranson (1999). They refer to the problem of an engineer having to project a new bridge. Simple and elegant models of the new bridge can be formulated, on the basis of Newtonian Physics. However, since nature is much more complicated to be captured by a small model, and different conditions of soil, changing weather, seismic waves and many other characteristics of the place matter, every bridge project undergoes extensive computer simulations before construction is started.

«When Nagel and Schreckenberg presented their cellular automaton model of traffic flow in 1992, allowing for a more than real-time simulation of the entire road system of large cities, they probably did not anticipate the resulting flood of publications and the enthusiasm among scientists on the subject of traffic theory. By treating huge numbers of interacting vehicles similar to classical many-particle systems, physicists have recently contributed to a better understanding of traffic flow. The mathematical tools that they use, stemming mainly from statistical physics and nonlinear dynamics, have proved their interdisciplinary value many times» (Helbing and Treiber, 1998).

Transport simulation models are now common. As an example, CORSIM - a computer simulation model of street and highway traffic - is the quasi-official platform used by the U.S. Department of Transportation (USDOT) to gauge traffic behaviour and compare competing strategies for signal control before implementing them in the field (USDOT FHWA, 1996). Other leading micro-simulators of traffic dynamics include

AIMSUN (Barcelò et al., 2003) and PARAMICS (Duncan, 1995). A survey of agent-based traffic simulators can be found in Erol (1998).

The purpose of the present paper is much less general than the works reviewed here. I do not want to build a comprehensive model of traffic behaviour, neither I wish to contribute to a more general theory of driving attitudes, by considering the endogenous character of some relevant variable. I simply want to investigate the effects of a small change in the (external) driving rules. This work has some features of the traffic engineering literature, due to the attention to the dynamic properties of the model, but relies on a number of strongly simplifying assumptions, as often done by economists. In particular, I abstract altogether from car following considerations. The distance between a vehicle and its leader is kept constant. While this assumption may of course be criticised, I believe it is appropriate for the purpose of the work. I do not see any reason why including a variable car following specification should modify the results of the study. Moreover, I relax this assumption in a later section, by allowing the possibility of crashing into a leading vehicle and assuming it depends on the *decrease* in speed of the other vehicle, and I do not find any change in the simulation results. However, the effects of introducing a more realistic car following theory in the model should be tested. This is left for future developments. Speed choice is also very stylised. All vehicles have different desired speed. They never go faster than that. They decelerate only when some slower vehicle is on the way, if it is not possible to pass it. The next section introduces the simulation set-up more in details.

Finally, there is a story that could be told to defend this extremely simplified nature of the model. I proposed some traffic engineers to test in their simulation models the effects of the change in the Road Code investigated here. They were very interested but refused, since – they said – making the appropriate modifications in the lane change rules embedded in their model would have taken weeks of an expert programmer's time!

2. The simulation

In order to compare the performances of the two rules, I develop an agent-based discrete-time simulation, written in java code using JAS libraries, developed by Michele Sonnessa at the University of Torino (http://jaslibrary.sourceforge.net). Two 3-lane motorways are simulated. At each time period, *n* new vehicles are created. Each vehicle is instantiated in two copies: one enters the old rule motorway, the other one the new rule motorway. Then, all vehicles are moved. Although in reality all vehicles move at the same time, the nature of the simulation requires the vehicles to be moved sequentially. Front vehicles are then moved first; among adjacent vehicles, those on the farther left lane are moved first.

2.1 Motorways

The two motorways are essentially a grid, with a predefined length and a width of 3 cells (the three lanes). Vehicles can move right, forward or left, but they obviously cannot move backwards.

2.2 Vehicle characteristics

Each vehicle has an exogenous desired speed, $\underline{s_i}$. If possible, at each time period it moves forward of exactly s_i cells. Vehicles with a desired speed below s_{slow} are considered slow, and in the old rule motorway have to follow the indications for slow vehicles.

Let's define *r*, *m* and *l* as the maximum distance that can be covered on the three lanes (the right, middle and left lane). If no other vehicles are on the way, $r = m = l = \underline{s_i}$. If for instance a vehicle is on the right lane, just one cell forward, then $r = 0$. A vehicle is currently at position (x_t, y_t), where y is the lane and x the distance from the origin. After the move, the vehicle is at (x_{t+1}, y_{t+1}), with $x_{t+1} = x_t + s$, s being the actual vehicle speed.

The distribution of the desired speed is uniform between s_{min} and s_{max}. The introduction of a speed limit constrains all vehicles with a greater desired speed to the limit, thus increasing the density at the maximum allowed speed.

New vehicles are given a random x position between 0 and s_{max}, and are randomly assigned either to the middle or to the right lane. They are placed on the grid only if their position corresponds to a free cell. Thus, the actual number of vehicles entering the motorway each period can be lower than n, while the maximum number of vehicles that could in theory enter the motorway each period is $2 \cdot s_{max}$.

2.3 Passing rules

Vehicles behaviour changes according to the different rules. For the sake of clarity, I distinguish three cases for each rule, depending on the lane currently occupied by the vehicle.

2.3.1 New rule

(r) right lane:

(r.1) if straight is free, move forward, with speed $s = min(r,m,l)$[1]

(r.2) if straight is not free, move left (on the middle lane), with speed $s = min(m,l)$

(m) middle lane:

(m.1) if straight is free, and right is free, move right, with speed $s = l$

(m.2) if straight is free, but right is not free, move forward, with speed $s = l$

(m.3) if straight is not free, move left, with speed $s = l$

(l) left lane:

(l.1) if right is free, and straight is free, move right (on the middle lane), with speed $s = l$ $= m$

(l.2) else, move forward, with speed $s = l$

2.3.2 Old rule, fast vehicles

(r) right lane:

(r.1) if straight is free, move forward, with speed $s = min(r,m,l)$

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[1] since no right pass is permitted, the position of the closest vehicle on the middle lane limits how far a vehicle on the right lane can go.

(r.2) if straight is not free, move left (on the middle lane), with speed $s = min(m,l)$

(m) middle lane, fast vehicle
(m.1) if straight is free, move forward, with speed $s = l$
(m.2) if straight is not free, move left, with speed $s = l$

(l) left lane:
(l.1) if right is free, and straight is free, move right (on the middle lane), with speed $s = l$ $= m$
(l.2) else, move forward, with speed $s = l$

The only difference with respect to the new rule is that here fast vehicles on the middle lane do not move on the right lane, even when it is empty.

2.3.3 Old rule, slow vehicles
(r) right lane:
(r.1) if straight is free, move forward, with speed $s = min(r,m,l)$
(r.2) if straight is not free, move left (on the middle lane), with speed $s = min(m,l)$

(m) middle lane:
(m.1) if straight is free, and right is free, move right, with speed $s = l$
(m.2) if straight is free, but right is not free, move forward, with speed $s = l$
(m.3) if straight is full, move forward, with speed $s = min(m,l)$

2.4 Accidents

Accidents occur because when a vehicle moves right or left, with a probability p it does not look properly whether there is any other vehicle on its immediate right or left. Suppose a vehicle is on the middle lane at (x, m) and wants to move left, because some other vehicle is on its way on the middle lane. If such a distraction occurs, it may have no consequences, in case no other vehicle is on (x, l), or it may cause an accident, in case the cell (x, l) is occupied. Note that the probability of a distraction is exogenously

defined, and thus independent of the speed of the two vehicles that could be involved in the accident. This is clearly a simplification, and will be relaxed later on. Note also that there are no other possibilities to cause an accident. In particular, it is not possible to bump into a slower vehicle driving ahead. Again, this is a simplification, and will be relaxed by allowing such a possibility, and by letting it be dependent of the vehicle speed and the front vehicle *variation* in speed (i.e. by considering explicitly the danger of slow-downs).

Vehicles involved in accidents are immediately removed from the motorways, and thus do not cause queues or delays. Again, this is not realistic; however, since it will be shown that the new rule leads to more accidents, the introduction of negative accident externalities would push even more the results in favour of the old rule.

3. Simulation results

In the simulation output presented below, 1 period is meant to last 1 minute. Since normally freeways cannot sustain a flux of more than 2,000 vehicles per hour per lane[2], this means that the influx of new vehicles must be constrained to an upper bound of 100 vehicles per period (6,000 vehicles per hour). Cells length has no implication whatsoever in the model. The reader could suppose each cell to be 50 metres long, or 100 metres long, as preferred. Desired speed is uniformly distributed between 80 and 160 km/h, but is constrained to a maximum of 130 km/h by the speed limit. A distraction probability of 0.01 (i.e. one in a hundred probability of changing lane without looking) is considered, while the entry rate is set at 50 vehicles per period. This value corresponds to medium traffic conditions. Vehicles with a desired speed below 90 km/h are considered to be 'slow'. Changing the value of the distraction probability affects the slope of both curves for the total number of accidents, but not their relative

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[2] Urban freeways are able to sustain a higher flux of around 2,500-3,000 vehicles per hour per lane, because drivers "learn" that in order to go (collectively) faster they have to restrain from passing slower vehicles! These estimates have been provided verbally by transport engineers at CSST - Centro Studi sui Sistemi di Trasporto - a private Turin based company involved in research, planning and engineering applied to travellers and freight transport systems.

slope (the coefficient of an OLS regression of the ratio of the total number of accidents with the two rules on the distraction probability is not significantly different from 0). Here, the capacities of the two motorways look similar. However, by increasing further the entry rate to heavy or very heavy traffic conditions, or by considering a higher threshold for slow vehicles, the old rule motorway starts performing better also with respect to this indicator.

In general, the only situation when the new rule performs better that the old one is when there are no slow vehicles, or an extremely small number of slow vehicles. In this case, we are actually comparing a 3-lane motorway (the new rule) with a 2-lane motorway (the old rule). Average speed and capacity are obviously higher in the 3-lane motorway, although the number of accidents is of course also higher (the best thing to avoid motorway accidents is not driving on motorways at all!). However, even with a small increase in the number of slow vehicles, the results change in favour of the old rule. In the example presented above, to have the new rule outperform the old one in terms of number of accidents the low speed threshold has to be moved down to 85 km/h!

Figure 1: Simulation results – benchmark case
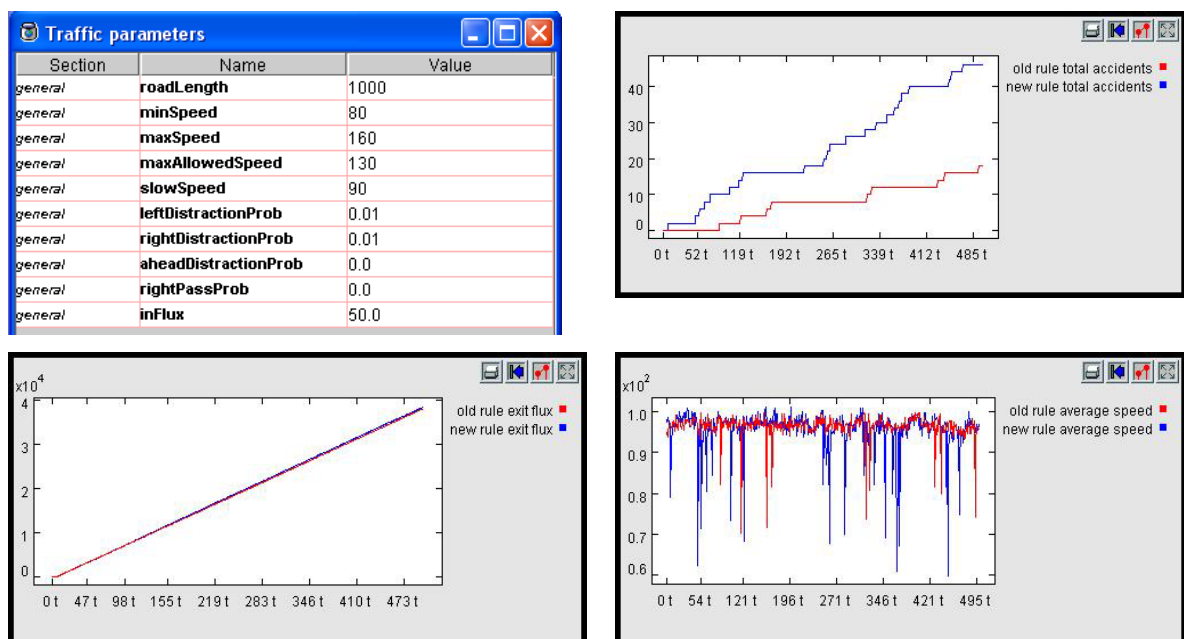
Note that not only the average speed with the new rule is lower, but also there are more slow-downs. The two situations are described by the 'helicopter view' provided below. Each coloured point represents one vehicle. Vehicles in red have just had an accident, and are going to be removed without any inconvenience for other cars. The trait below is an over-crowded part of the motorway, which looks freer in other traits.

Figure 2: Helicopter view of the two motorways
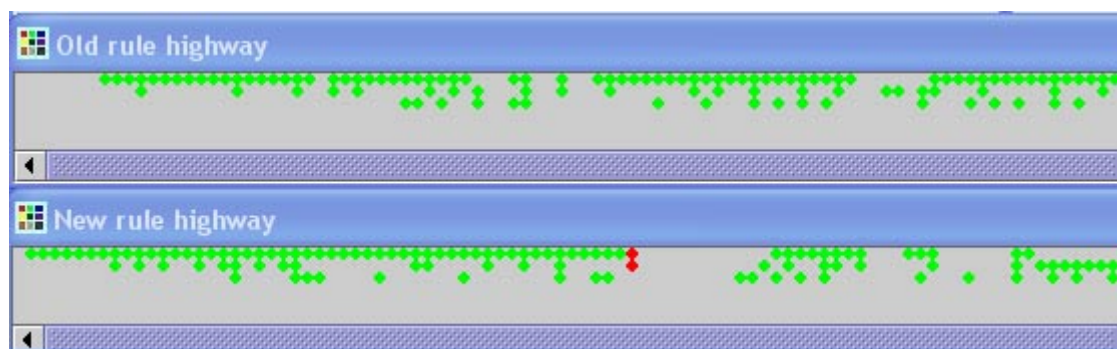
How is this (at first striking) result possible? Doesn't the new rule allow a more rational use of the highway? The answer is: the new rule implies many more lane changes than the old rule. In the model, lane changes are the only possible sources of accidents, hence the result, in terms of accidents. Moreover, when a fast vehicle moves right in heavy traffic, it can remain 'trapped' behind a slower vehicle, unable to pass it because of other vehicles approaching on the pass lane. This justifies the result in terms of slower capacity. Note that these conclusions are not trivial. Supporters of the new rule could argue that, if everybody moves right whenever possible, the probability of a pass lane being occupied should go down. Thus distractions should have fatal consequences less frequently, and the probability of being 'trapped' in slow lanes should also diminish. This is true, but as the traffic becomes heavier, a small frequency of slow vehicles is enough to overturn this argument, and make the old rule outperform the new one.

The graphs below show what happens to the ratio of the relevant variables with the new and the old rule, as the entry rate is increased: a ratio of 1 means the two values are the

same. In the first graph average speed is considered. For low traffic the value of the ratio is around unity (the old rule and the new one perform roughly the same), but it keeps decreasing as the traffic gets heavier. Total accidents are shown in the second graph. The value of the ratio is generally well above unity, meaning the new rule is characterized by more accidents. As traffic increases, the differences between the two rules diminish (eventually, when there is no more room vacant, the two rules generate a roughly equivalent number of accidents). Finally, the last graph shows the old rule outperforming the new one also in terms of the exit rate of vehicles.
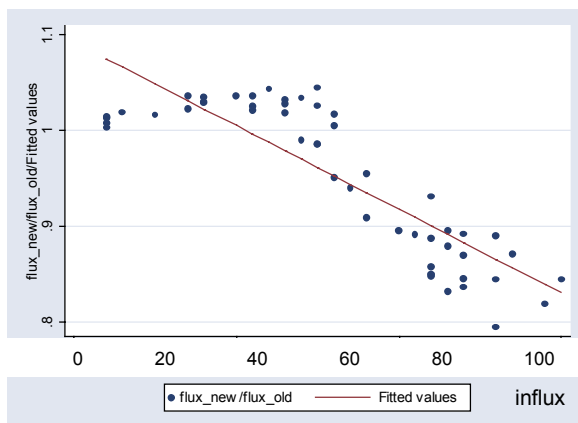
Figure 3: Traffic conditions effects – reference model
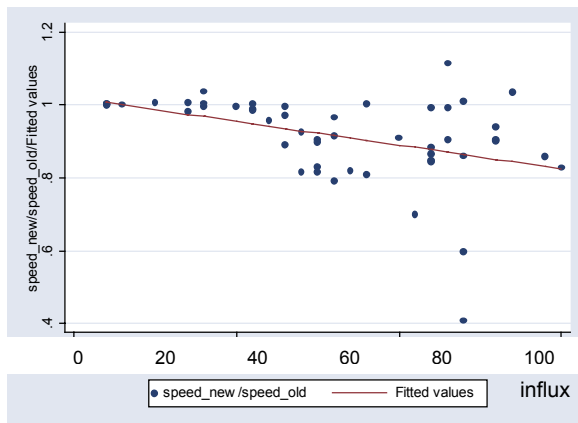
(a) Average speed
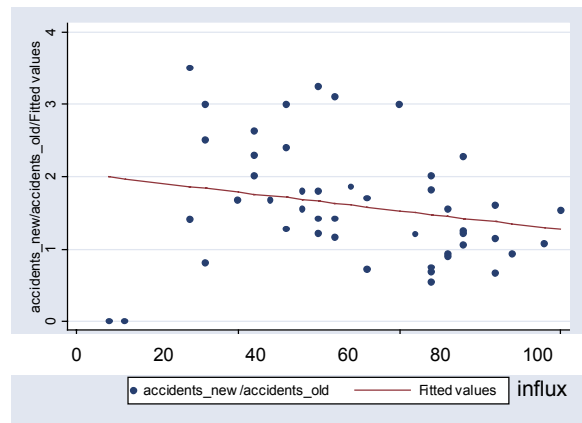
(b) Total number of accidents

(c) Exit rate

Continuous line represents fitted values from a simple OLS regression of the dependent variable on the independent one

The main objection to the analysis above is that the superiority of the old rule stands from considering only lane changes as a cause for accidents. Note first that also in the real world lane changes are a major source of troubles. However, in the next sections I will refine the stochastic modelling of accidents, in order to test the robustness of the conclusions presented here.

4. Right pass

Supporters of the new rule say that the old one had the disadvantage of induce drivers in temptation. The main temptation, when there is a slow vehicle ahead and no room for a proper pass on the left, being of course a right pass. With the new rule, there should be no vehicles at all leaving empty space on their right, or at least there should be less incentive to break the law and do a right pass. But how much less? Is this sufficient to overturn the advantage of the old rule, as described in the previous section? In order to answer to this question, I have added a (small) probability of performing a right pass, in case the left lane is full but the right one is free. As expected, the new rule now performs better, relatively to the old one. However, even by assuming a very high propensity for right passes, the old rule generally remains better. The reason is that, even with the new rule, the incentives for a right pass do not vanish completely. Suppose for instance there is a slow vehicle far ahead, with many cars queuing to pass it on the left. The respectful driver should slow down, move to the left and wait for his turn to pass the slow vehicle. However, he may found convenient to go straight ahead, right-pass all vehicles on his left, and finally move to the left only when he eventually reaches the slow vehicle ahead.

To make the simulation more realistic, the introduction of a propensity for right passes is assumed to increase the probability of a distraction when moving right (but not when moving left). The graphs below depict a situation with a left-move distraction probability of 1/1000, a right-move distraction probability 5 times higher (5/1000), and a right-pass propensity of 0.25 (drivers pass on the right one quarter of the times this allows them to pass a forehead vehicle, when no left pass is possible). Other parameter

values are the same as in figure 1. Ideally, we would like to see values of the ratio above 1 for the average speed, below 1 for the number of accidents, and again above 1 for the exit rate, meaning the new rule is better than the old one in all respects. Unfortunately, exactly the opposite happens. Above a certain traffic density, the old rule still outperforms the new one. Only when the traffic density is low the new one is less accident-prone than the old one, although for what concerns average speed they look roughly equivalent. Different values of the relevant parameters do not alter qualitatively the results.
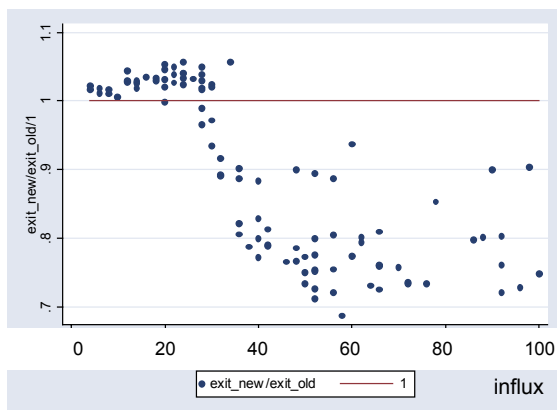
Figure 4: Traffic conditions effect – right pass considered
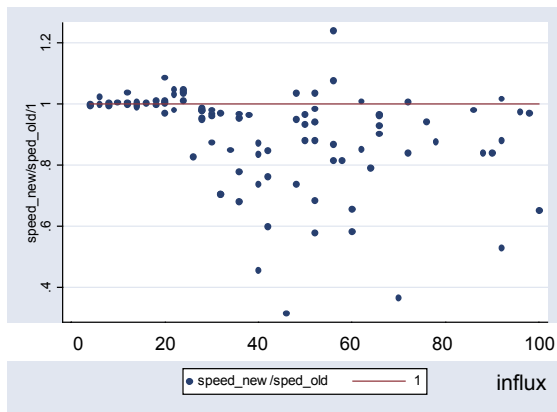
(a) Average speed
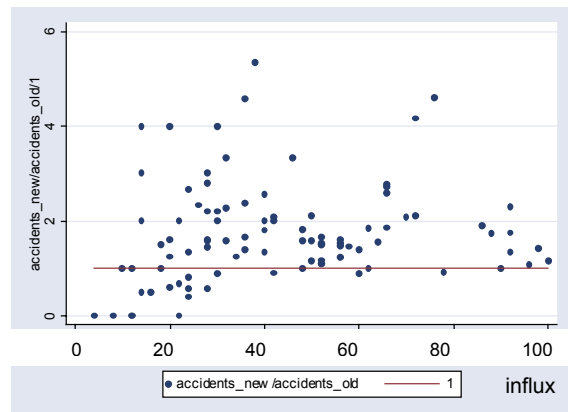
(b) Total number of accidents

(c) Exit rate

Continuous line represents value of the ratio = 1

5. Speed dependent distraction probabilities

In this section, I keep on adding realism to the simulation by considering that the probability of having an accident is higher when driving faster. Actually, it is not obvious that the distraction probability should be higher for faster vehicles, since drivers could pay more attention. However, the consequences of an accident are obviously more severe, the faster the cars involved. Since it would be not worthy to introduce a distinction between different types of accidents, the model simply mimics this by considering that faster vehicles are more accident-prone, i.e. they have a higher distraction probability. This is also in line with the predictions of the speed choice theory, as outlined above. It is assumed that the distraction probability increases with the square of the actual speed:

[1]
$$p_i = p \cdot \left(\frac{s_i}{s_{max}} \right)^2$$

where p_i is the individual distraction probability, p the reference value for the distraction probability (which is attributed to cars driving at the maximum speed s_{max}) and s is the individual speed. This means that a car driving at 80 km/h has only a quarter of the risk of a car driving at the maximum speed of 160 km/h, while for a car driving at 120 km/h the risk has already jumped up to more than 55%.

In terms of accidents, the new rule seems now to be a little closer to the old one (since with the old one the average speed was higher), if only in heavy traffic conditions. In light and medium conditions the old one is still associated with about a half the number of accidents.
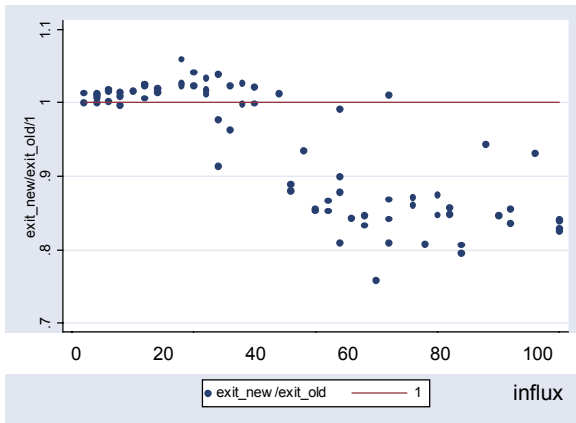
Figure 5: Traffic conditions effect – speed-dependent accident probability
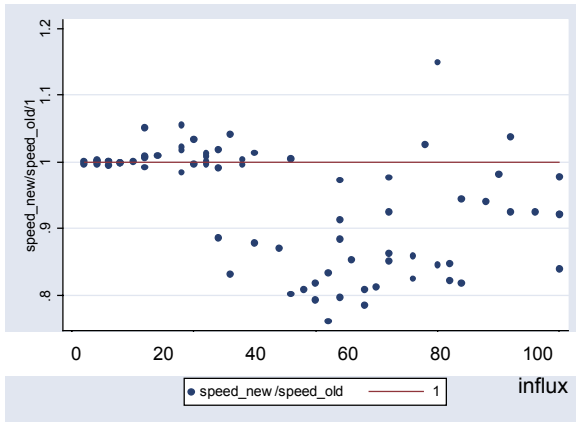
(a) Average speed
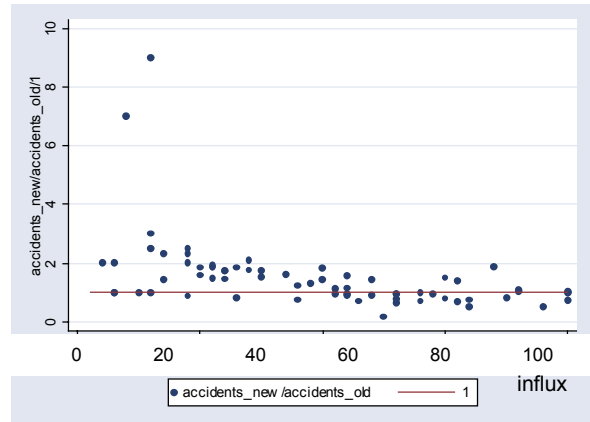
(b) Total number of accidents

(c) Exit rate

Continuous line represents value of the ratio = 1

6. Front crashes

The last extension of the model considers the possibility of crashing into vehicles ahead. For the sake of realism, this probability is assumed to depend on the *decrease* in speed of the other vehicle:

[2]

$$p_i = \begin{cases} p \cdot \left(1 - \left(\dfrac{s_{i,t-1}}{s_{i,t}}\right)^2\right) & s_{i,t-1} \geq s_{i,t} \\ 0 & s_{i,t-1} < s_{i,t} \end{cases}$$

where p is the reference value for the distraction probability. For instance, if a vehicle j ahead decreases its speed from 130 km/h to 100 km/h, the probability of vehicle i crashing into it is around *0.41 p*, while if vehicle j has reduced only to 110, the probability goes down to a mere *0.28 p*.

However, allowing front crashes doesn't make the new rule appear any better. The intuition is simple: since the new rule causes more slow-downs, as described in section 2 above, according to [2] the probability of not seeing a vehicle ahead is reducing speed is higher than with the old rule. Moreover, if all vehicles have to drive as much on the right as they can, it becomes more likely to have someone on the way ahead, in the same lane. Simulations confirm this intuition.

7. Summary and conclusions

In July 2003 a new Road Code was approved by the Italian parliament. Among many reforms whose validity is not questioned here, the new law states that on three-lane motorways the right lane should not be reserved anymore to slow vehicles alone. As in two-lane roads, all vehicles must now drive on the right lane, as long as it is not occupied by other vehicles. The model developed in this paper is an agent-based model, characterised by a very simple speed choice rule (each vehicle goes at its desired speed unless forced to decelerate because some slower vehicle is on the way) and without explicit modelling of car following (the distance from the preceding vehicles is kept constant but in the last section, when the possibility of crashing into vehicles ahead is considered). Simulation results cast doubts on the validity of the change, suggesting that the old rule generally performs better, in terms of number of accidents, average speed and motorway capacity, than the new one. This conclusion is shown to be extremely

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robust to refinements of the main assumptions concerning driving attitudes and the stochastic arrival of accidents.

The main strength of this model is also its main limit: simplicity. Assumptions about speed choice do not seem to be a cause of trouble. After all, they are not so unrealistic. Instead of deriving the 'desired' speed as the solution of an optimisation problem, like often done in the economic literature, its distribution is assumed from the outside. Moreover, it is quite reasonable to assume that when there is no room to pass, one has to slow down to the speed of the preceding vehicle. It is true that vehicles that wish to move faster normally adopt a more aggressive driving attitude. However, I believe that this could be left out of a simple model, without great backdrops. Assumptions about car following are more questionable. In particular, introducing more sophisticated car following specifications could help in modelling the stop-and-go effects of the two rules. However, since it is shown that the new rule produces more variance in the speed of the vehicles, it is likely that having a better model for car following would even sharpen the results of the analysis. A test of this claim, however, should be performed in an expanded version of the model, which is left for future developments.

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