Traffic Flow Simulation Dovetailed with Evolutionary Game Theory

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Abstract: Previous work (Yamauchi et al., *PRE* 79 and Nakata et al., *Physica A* 389) found several social-dilemma structures in phases of traffic flows created by bottlenecks resulting from lane closings. We investigate another question: whether or not such structures can be formed from frequent lane changes in a usual traffic flow without any explicit bottlenecks. In our model system, two classes of driver-agents coexist: C-agents (cooperative strategy) always remain in the lane they are initially assigned, while D-agents (defective strategy) try to change lanes to move ahead. In relatively high-density flows, such as the metastable and high-density phases, we found structures that correspond to either n-person Prisoner's Dilemma (n-PD) games or to quasi-PD games. In these situations, lane changes by D-agents create heavy traffic jams that reduce social efficiency.

1 INTRODUCTION

In growing social concerns on traffic problems, there have been lots of previous studies dealing with the so-called traffic model (e.g. Kerner, 2009). Especially, it has struck many statistical physicists as interesting, just because a traffic flow can be interrupted as a self-driven multi-particles system. In that particular sense, among several traffic models such as the kinetic gas theory, fluid dynamical model, car-following model, cellular automaton (CA) model has been most heavily concerned. However, none of these previous studies provided a comprehensive understanding on real traffic flow phenomena because these models did not include the decision-making process of the drivers. If we recognize that the traffic flow results from competition for a finite resource ("road") among many drivers who are seeking shorter driving times and more comfortable driving, it is natural to ask whether or not a social dilemma originates from the intentions of drivers. If so, we question the class of dilemma, such as the Prisoner's Dilemma (PD) game, Chicken (Snow Drift) game, or something additional, lies hidden beneath the observed traffic flow and performs the game change when the flow changes from one kind of phase to another. With this background, we detected that several social dilemma structures, represented by n-person Prisoner's Dilemma (n-PD) games, appear in certain traffic flow phases at a bottleneck caused by a lane closing (Yamauchi et al., 2009; Nakata et al., 2010). We confirmed that an n-PD game structure appears in the high-density phase area, but no social dilemma exists in the free-flow and jam phases. It seems plausible for a social dilemma to underlie such traffic flows because closing a lane creates an obvious bottleneck. Thus, our next challenge is whether a social dilemma still lies beneath traffic flow that does not involve any explicit bottleneck like a lane closing, on-ramp (merging), off-ramp (exit), or uphill travel. This paper addresses whether or not only lane-changing actions by drivers can give rise to a social dilemma in an ordinal two-lane road system with cyclic boundaries.

2 MODEL SETUP

We applied the Revised S-NFS model (Kokubo, 2011) for driving vehicles forward. Revised S-NFS model takes into account motions that are commonly observed in real vehicles: slow-to-start (S2S), quick start (QS), and random braking (RB). S2S implies an inertial effect, which is important for producing metastable states in fundamental diagrams, also improve reproducibility of the so-called three-phase theory by Kerner (2009).

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We applied the lane-changing rule used by Kukida et al. (2009) in the CA model.
Concerning Revised S-NFS model and Kukida's lane change model, we assumed a set of model parameters to reproduce realistic traffic flow. Also we set the system length to L = 500.

In the system there are two types of agents: cooperators (C-agents) remain in the lane initially assigned without making any lane changes, and defectors (D-agents) change lanes. We denote fraction of cooperators among all agents by P_c. We use cyclic boundary conditions to keep the vehicle density constant during a single simulation episode.

3 RESULT AND DISCUSSION

Figure 1 shows fundamental diagrams for (a) Pc = 1 and (b) Pc = 0 in which each dilemma class discussed below is identified by a different color. Figure 1(a) shows that flows of all cooperators can exhibit the so-called metastable phase, while Figure 1(b) shows that no metastable phase occurs in flows of all defectors. This seems plausible because a flow in relatively high-density regions can be stable with high traffic flux so long as none of the vehicles change lanes. In contrast, a flow with lane changes becomes volatile, since turbulence caused by frequent lane changes promotes traffic jams. Behaviors of the observed dilemma classes are explicitly discussed below; here, we merely note that only the Prisoner's Dilemma (including quasi-PD and quasi-little PD) class appears in the middle density region with relatively high traffic fluxes. The Trivial game and Neutral game also appear there, but these are not categories of social dilemmas.
Figure 2 shows the payoff functions and velocity frequencies for Case A in Figure 1(a) ($\rho = 0.1$), which is in the free-flow phase. Panel 2(a) shows that all payoffs for Case A are insensitive to the cooperation fraction; this implies a kind of gameless situation. So we denote this as a Neutral game class. This is not surprising because most of the vehicles in Case A run at maximum velocity (see Panel 2(b)), so lane changes in the system are rare.

Figures 3 to 9 show counterparts of Figure 2 for the other cases explicitly marked in Figure 1(a). The situation in Figure 3 ($\rho = 0.141$) can be called a Trivial game because Nash equilibrium (NE) accords with the Equal Pareto Optimum (EPO) at P_c = 0. This game is dominated by defection, since the defector's payoff is always larger than that of the cooperator. However, the maximum social payoff also appears at all defector states. In a nutshell, we call this a D-dominate Trivial game, which implies that more frequent lane changing is preferable in this density region from both social and individual points of view.

Figures 5 ($\rho = 0.179$) and 9 ($\rho = 0.6$) show the same tendencies as in Figure 3. Thus, all these should be classified as D-dominate Trivial games. The fact that the jam phase belongs to the D-dominate Trivial game (Fig. 9) seems reasonable because lane changes into even a slightly small vacant space between jamming vehicles brings

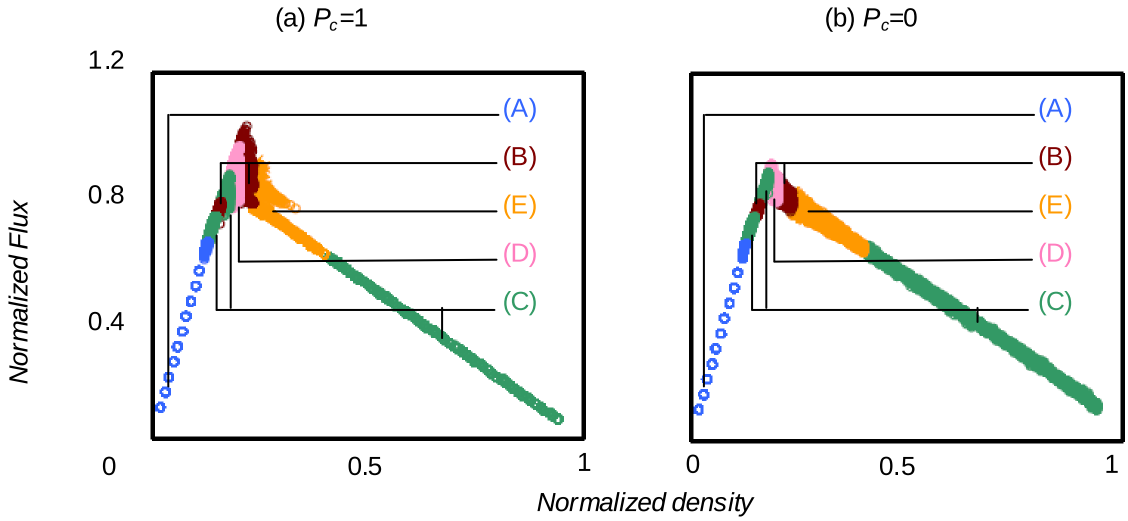

Figure 1: Fundamental diagrams (normalized flux vs normalized density) for situations with (a) all cooperators (P_c = 1) and (b) all defectors (P_c =0). Colored symbols identify (A) Neutral game, (B) Prisoner's Dilemma game at two densities in Panels (a) and (b), (C) D-dominate Trivial game at three densities in Panels (a) and (b), (D) D-dominate quasi-PD game, and (E) D-dominate quasi-light-PD game .

benefits for not only the focal vehicle who changes lanes but also for the society as a whole, even if its frequency is low.

Figure 4 ($\rho = 0.155$) suggests a weak Prisoner's Dilemma (PD). This is confirmed by the following facts. At $P_c = 0$, NE is trapped because the defector's payoff is always greater than that of the cooperator. EPO appears at $P_c = 1$ because the social payoff increases with increasing cooperation fraction, although the effect is subtle. The same tendency appears in Figure 7 ($\rho = 0.211$), although the extent of this dilemma seems more severe than that in Figure 4. In Figure 7, the social payoff function does not monotonically increase with the increase in the cooperation fraction, as observed in Figure 4; rather, it shows an N-character shape, in which a local peak (much smaller than EPO at $P_c = 1$) appears at a lower cooperation fraction. This point is carefully discussed in Sec. 3.2.

Figure 6 ($\rho = 0.194$) differs slightly from the simple PD because EPO is not observed at $P_c = 1$, although NE is trapped at $P_c = 0$. At any rate, EPO is largely inconsistent with NE since EPO, which is the peak of social payoff, appears above $P_c = 0.5$. Therefore, we call this game structure a D-dominate quasi-Prisoner's Dilemma game.

Figure 8 ($\rho = 0.244$) seems odd; it looks analogous to a D-dominate quasi-PD Game (Fig. 6), but it differs. EPO defined by the peak of social payoff appears below $P_c = 0.5$ and is relatively close to NE found at $P_c = 0$. Therefore, we call this a D-dominate quasi-light PD game.

Figure 10 shows the effects of vehicle density on the strength of dilemma, η, defined by Nakata et al. (2011). Figure 10 shows that the density at severe dilemma strength is consistent with the density observed in the high-flux region, including the metastable phase (Fig.1 (a)). This seems physically plausible because, in this density region, a driver has a strong incentive for changing lanes to exploit other drivers and ensure his own benefit is maximized (smaller travel time). However, when one driver changes lanes, others might follow. Therefore, states with high flux, say in the metastable phase, collapse with the phase shifting to the jam phase.

4 CONCLUSIONS

For ordinal traffic flows, we have successfully demonstrated that there are hidden social-dilemma structures evoked by drivers' decisions whether or not they should change lanes. This was confirmed by a series of numerical simulations using the revised S-NFS cellular automaton model combined with a lane-changing model that we developed and applied with cyclic boundary conditions.

Interestingly, social dilemmas, as classified by the Prisoner's Dilemma game or its variants, were only observed in situations of middle vehicle density; these situations correspond to the region on the fundamental diagram, including the metastable phase, in which data are scattered. This seems plausible because, when a driver is surrounded by other vehicles, that driver has a serious incentive to change lanes. However, if all drivers make the same decision, social efficiency declines phenomenally and huge traffic jams emerge. We also evaluated the relation between dilemma strength and density of vehicles.

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APPENDIX

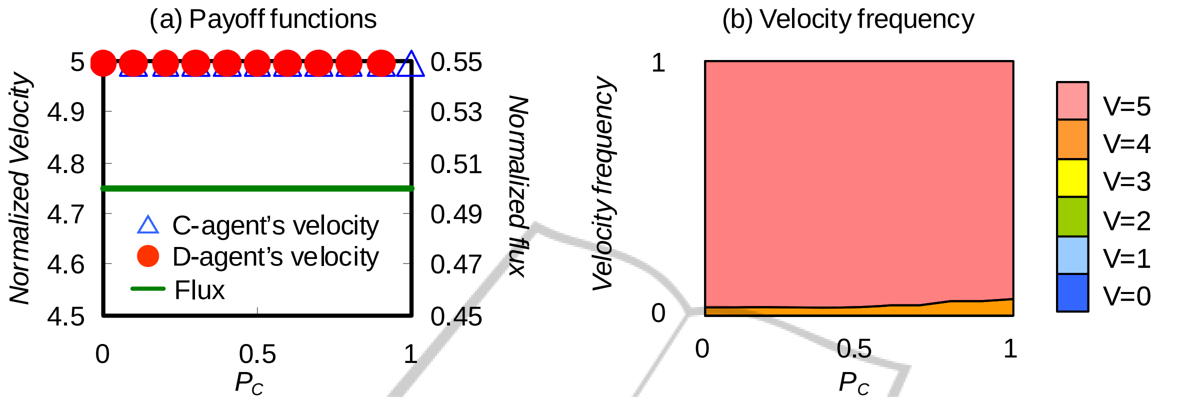

Figure 2: Results for $\rho = 0.1$ at point A in Figure 1(a). (a) Effect of fraction of cooperators (P_c) on payoff functions (velocity and flux). Red closed circles are average payoffs of defectors, and blue triangle are average payoffs of cooperators. Green bold line indicates traffic flux as a social payoff. (b) Effect of fraction of cooperators (P_c) on velocity frequency. This behavior corresponds to a Neutral game.

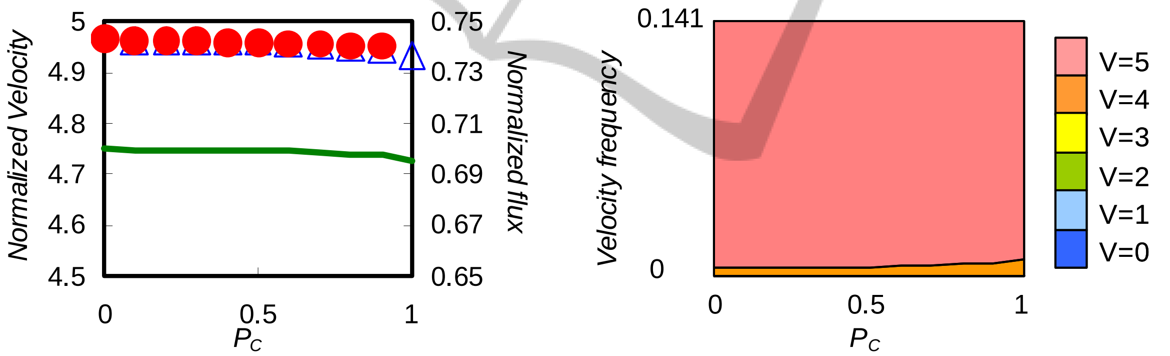

Figure 3: Same as in Figure 2, except at $\rho = 0.141$, which corresponds to one of the three points C in Figure 1(a). This behavior corresponds to a D-dominate Trivial game.

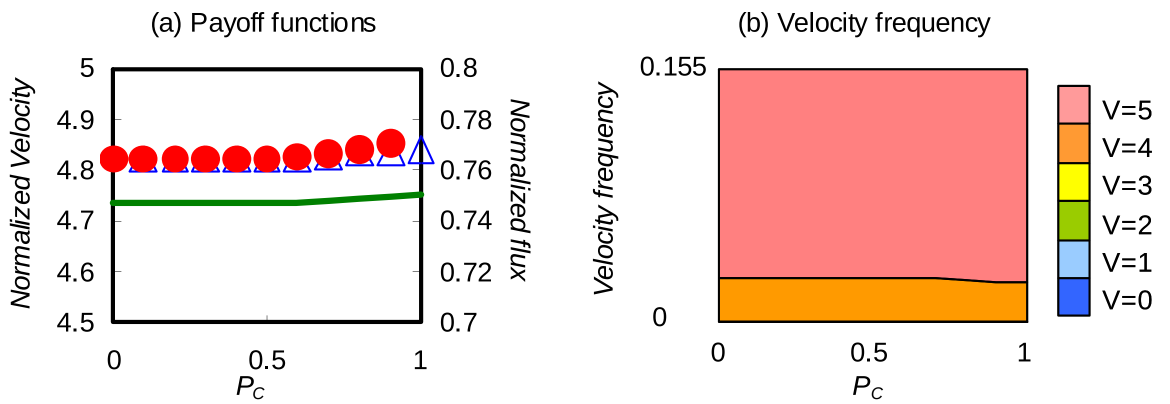

Figure 4: Same as in Figure 2, except at $\rho = 0.155$, which corresponds to one of the two points B in Figure 1(a). This behavior corresponds to a weak Prisoner's Dilemma game.

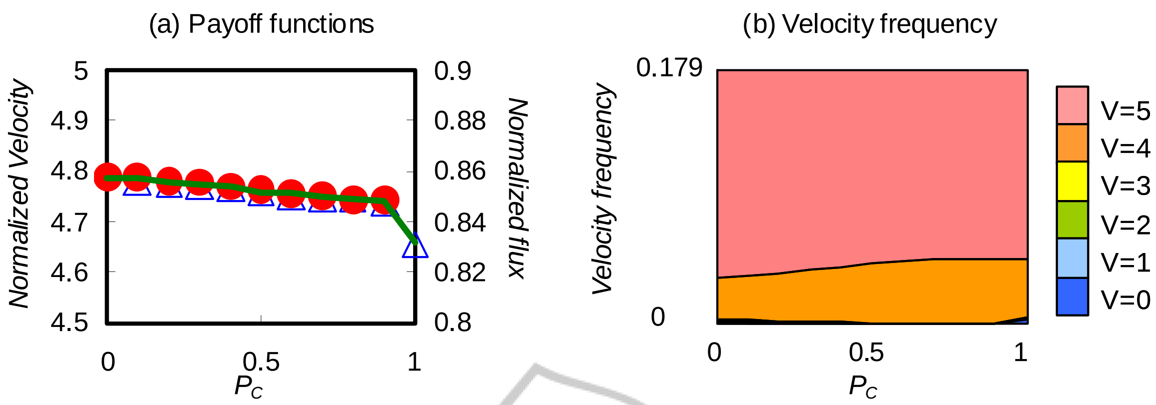

Figure 5: Same as in Figure 2, except at $\rho = 0.179$, which corresponds to one of the three points C in Figure 1(a). This behavior corresponds to a D-dominate Trivial game.

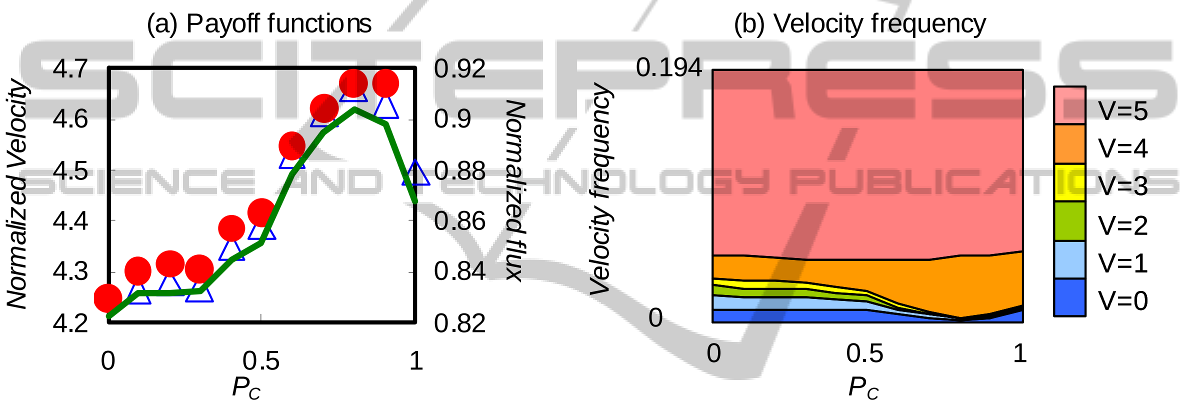

Figure 6: Same as in Figure 2, except at $\rho = 0.194$, which corresponds to point D in Figure 1(a). This behavior corresponds to a D-dominate quasi-Prisoner's Dilemma game.

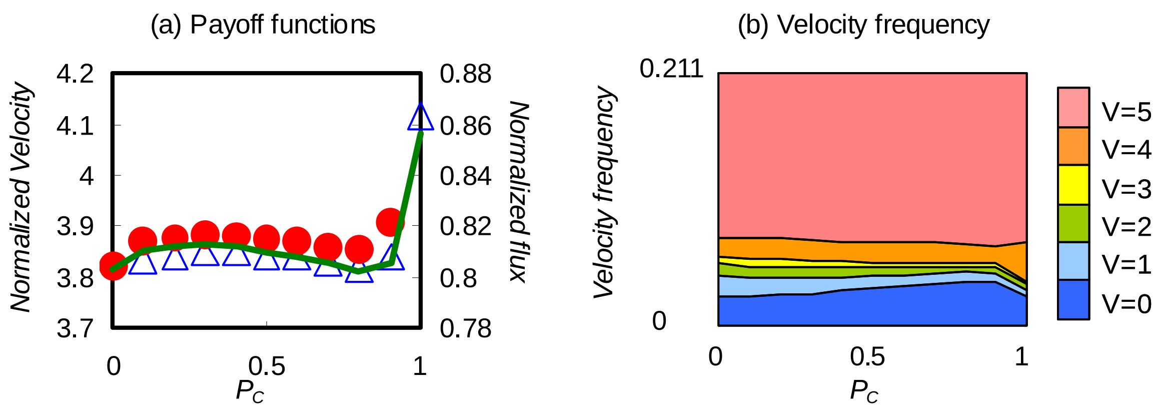

Figure 7: Same as in Figure 2, except at $\rho = 0.211$, which corresponds to one of the two points B in Figure 1(a). This behavior corresponds to a weak Prisoner's Dilemma game.

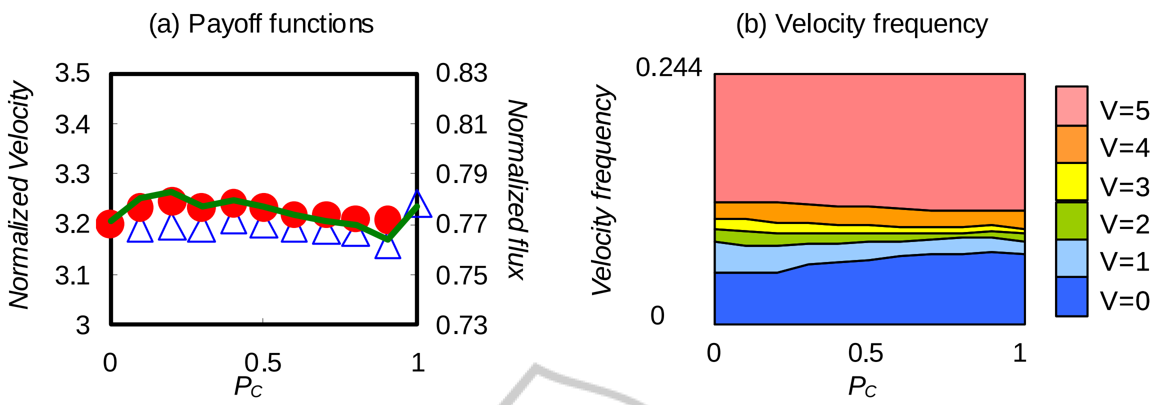

Figure 8: Same as in Figure 2, except at $\rho = 0.244$, which corresponds to point E in Figure 1(a). This behavior corresponds to a D-dominate quasi-light PD game.

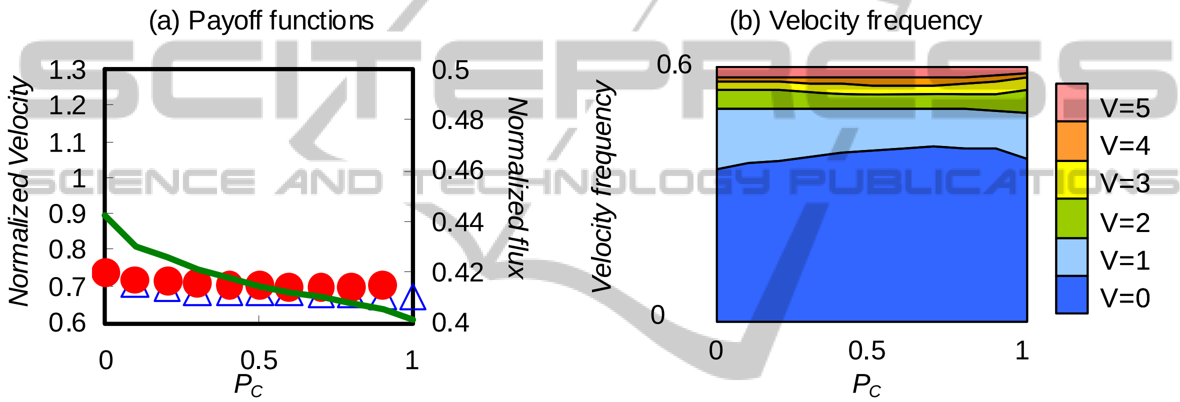

Figure 9: Same as in Figure 2, except at $\rho = 0.6$, which corresponds to one of the three points C in Figure 1(a). This behavior corresponds to a D-dominate Trivial game.

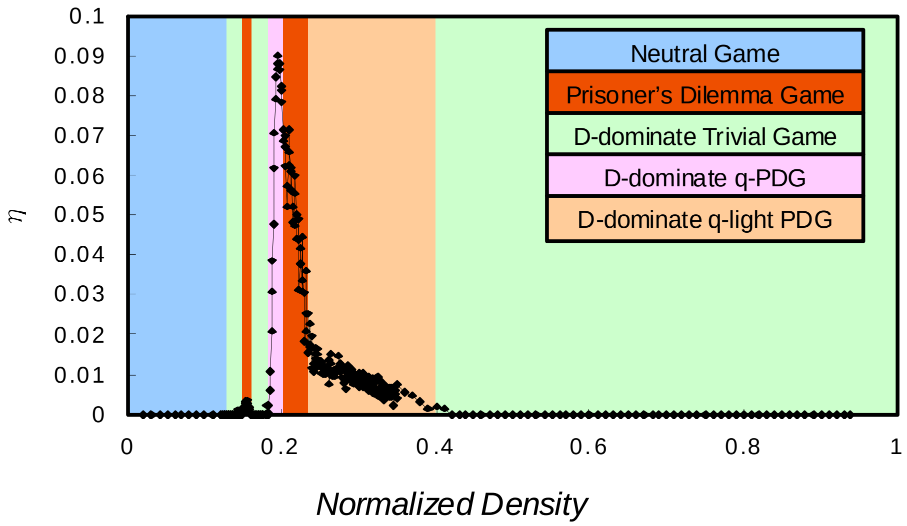

Figure 10: Effects of vehicle density on dilemma strength, η. Each color identifies one of the dilemma classses shown in Figure 1(a): (A) Neutral game, (B) Prisoner's Dilemma game, (C) D-dominate Trivial game, (D) D-dominate quasi-PD game, and (E) D-dominate quasi-light-PD game.