Equilibria in Routing Games With Connected Autonomous Vehicles Will Not Be Strong, as Exclusive Clubs May Form

Rafał Kucharski*[1], Natello Descormier[2], and Anastasia Psarou[1]

[1]Faculty of Mathematics and Informatics, Jagiellonian University, Poland
[2]École Polytechnique, Institut Polytechnique de Paris, France

Short summary

We examine whether route-choice equilibria remain stable once connected autonomous vehicles (CAVs) can coordinate their decisions. In classical traffic assignment, a user equilibrium is interpreted as a Wardrop or Nash-type equilibrium where no traveler can improve by changing route alone Wardrop (1952); Nash (1950). We show that this will be no longer sufficient when autonomous vehicles can communicate and deviate jointly. We formulate route-switching coalitions (*clubs*), define their internal and external stability, and demonstrate the formation mechanism in a microscopic mixed-traffic network with adaptive traffic signals. Starting from a user equilibrium, a three-vehicle CAV club can profitably deviate to another route, reduce each member's travel time, worsen conditions for excluded users, and increase the total travel time in the system. The results imply that CAV coordination may generate inequitable and strategically unstable traffic states on public road networks.
Keywords: autonomous vehicles; coalitions; route choice; strong equilibrium; traffic assignment

1 Introduction

User equilibrium has long served as the standard behavioural benchmark for route choice. Since Wardrop (1952), stating that network flows settle into a state in which no traveler can reduce travel time by unilaterally choosing a different route. In finite-player settings, this logic aligns closely with Nash equilibrium Nash (1950). The concept has been widely applied and accepted as it captures decentralized, self-interested routing behaviour without requiring any explicit coordination among travelers, serving as the backbone of classic transportation planning, traffic assignment, and congestion analysis.

That interpretation, however, depends on a strong behavioural premise: travelers must act effectively as isolated decision makers. Human drivers may exchange information, imitate successful behaviour, or respond to navigation applications, but their ability to form precise, enforceable, payoff-improving coalitions is limited. They lack perfect synchronization, shared information, and a mechanism for committing to collective deviations. Because of that, asking whether a road-network equilibrium is *strong* in the game-theoretic sense was pointless.

Connected autonomous vehicles may change this premise. A CAV fleet can observe network conditions in real time, share information instantly, and implement centrally coordinated routing decisions for many vehicles at once. These capabilities are usually discussed as efficiency-enhancing technologies, especially in settings such as platooning, merging, and signalized intersection management. Yet the same capabilities also create the strategic advantage. Once some vehicles can coordinate their routing decisions, the coalitions may start to form. A system may be strong with respect to individual deviations and still be vulnerable to an efficient collective deviations.

To better understand that possibility we experimentally ask whether route-choice equilibria in mixed traffic remain stable once part of the population consists of autonomous, connected, and coorindating vehicles. **The answer is negative. A user equilibrium may fail to be a strong equilibrium because a subset of CAVs can jointly switch**

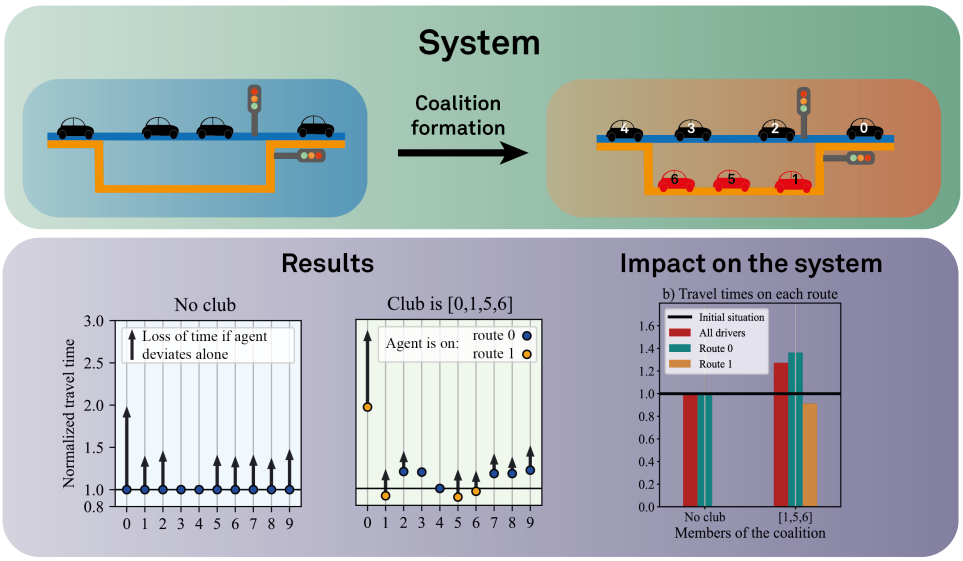


Figure 1: **CAV coalition formation.** We depart from User Equilibrium (top left) on a simple Two Route Network, where each driver decides to go straight (Route 0), as traveling Route 1 would be slower for each of them. When 10 out of 15 vehicles become autonomous vehicles, they reconsider their choices. None of them would benefit by individually deviating to Route 1 (bottom left); however, vehicles 1, 5, and 6 discover that by deviating together, they can arrive faster (bottom center). Not only on average, but also individually. Such benefit for the few invited club members is at the cost of other users and system performance (bottom right).

route and make every invited member better off. In this sense, as we demonastrate on an abstract scenario, connected vehicles can form *exclusive clubs*: small groups that exploit coordination to obtain lower travel times, while users outside the club bear the resulting costs.

The idea is closely related to strong-equilibrium reasoning in game theory. Aumann's notion of strong equilibrium rules out any coalition that can deviate in a way that benefits all its members Aumann (1959). Coalition-proof refinements later emphasized robustness to credible group deviations Bernheim et al. (1987). In transportation, by contrast, equilibrium analysis has focused far more on the gap between selfish outcomes and system optimum, often discussed via the price of anarchy Pigou (1920); Papadimitriou (2001); Roughgarden (2007). Here, we open a different concern: even if an observed state is a classical user equilibrium, it may still be not strong, once coordinated vehicle fleets appear.

The contribution is both conceptual and empirical. Conceptually, the paper translates strong-equilibrium ideas into route-choice language and defines a practical framework (algorithm) for identifying profitable clubs of autonomous vehicles. Empirically, it experimentally demonstrates the phenomenon in a minimal but realistic microscopic example built in SUMO Lopez et al. (2018). The example uses only two routes, fifteen travelers, and adaptive traffic signals, yet it is suffieint to exhibit the full logic of coalition formation, exclusion, and follow-up dynamics (Fig. 1).

The network is deliberately small so that the mechanism remains transparent. Ten of the fifteen vehicles are autonomous and able to coordinate. The five remaining vehicles are human-driven. The starting state is a user equilibrium in which all autonomous vehicles choose the default route. No single autonomous vehicle can improve by deviating alone. Nevertheless, an identified specific three-vehicle coalition can jointly switch to the alternative route and improve each member's travel time. This coordinated move worsens travel times for excluded users and increases the mean travel time in the system.

The result shows that route-choice equilibria not neccesarily will remain strong in mixed-

autonomy settings. Second, it exposes a fairness problem. Human-driven vehicles cannot realistically join such clubs, and even some autonomous vehicles may remain excluded as coalitions will be effeicient only up to a given size. Substantiating concerns about privileged access to public road networks' capacity.

2 Methodology

We study the problem as an atomic route-choice game with a finite set of travelers sharing the same origin and destination. A subset of travelers are CAVs, while the remainder are human-driven vehicles. Each autonomous vehicle can choose route. The initial state is a classical user-equilibrium profile in which no traveler can benefit from switching route alone.

We extend the analysis beyond unilateral deviations, defining a *club* as a coalition of autonomous vehicles that deviates jointly from the user equilibrium, such that it strictly improves the payoff of every club member. We introduce two properties fo such a club, to understand the phenomenon better. The first is *internal stability*. Once the club has formed, none of its members should want to leave by returning to the previous route. The second is *external stability*. Once the club has formed, no traveler outside the club should want to join by imitating its route change. These notions link naturally to strong equilibrium. If no profitable club exists from a given user equilibrium, then the equilibrium is strong with respect to the autonomous players. If at least one such club exists, the equilibrium is not strong. However, a profitable initial club does not necessarily determine the final state. Outsiders may wish to join after observing changed traffic conditions, which can trigger the new dynamics.

To represent such novel cascades, we propose a club-dynamics graph. The root node is an initially identified coalition. Directed edges then connect that coalition to new clubs obtained when outsiders have an incentive to join or leave. Terminal leaves correspond to natural candidates for post-deviation equilibria, which remain to be further understood.

Traffic outcomes are generated through microscopic simulation in SUMO Lopez et al. (2018) (Figure 1). It contains two routes from origin A to destination B, with a singalized junction with actuated control Smith (1979); Varaiya (2013); Gartner et al. (1991). Such supply-side response is essential, the coalition mechanism cannot arise solely because vehicles redistribute themselves between routes; it requires the traffic control system to react to the new flows. The essential property is that green time on the two routes changes with realized inflow. This makes it possible that a coordinated movement of several vehicles to the currently less-used route induces a control response favorable to that route. In effect, the coalition changes not only its own path choices but also the network conditions under which those choices are experienced.

The demonstrated case contains fifteen vehicles in total. Ten are autonomous and strategically active; five are human-driven and fixed to Route 0. The action space for the autonomous population therefore contains $2^{10} = 1024$ joint actions. For each joint action, we compute the resulting control setting, run the microscopic simulation, and record the travel time of each traveler. This produces a payoff matrix over all route-split configurations.

Operationally, club formation can be interpreted through a coordinating leader, such as a fleet operator or platform. The leader knows the precomputed payoff consequences of candidate joint actions and invites selected autonomous vehicles to deviate simultaneously. Such invitation-based logic matters, because the resulting coalition is exclusive by construction. Some users benefit because they are invited; others do not benefit because they are left outside.

3 Results

The main finding is that the baseline user equilibrium is *not* strong. Although no autonomous vehicle benefits from deviating unilaterally, one specific three-vehicle coalition, $\{1, 5, 6\}$, can move jointly to Route 1 and make every member better off. This is the key proof-of-concept result: classical route-choice equilibrium can fail once coordinated CAV deviations are allowed.

Table 1 reports the core payoff comparison. In the baseline equilibrium x^0, vehicles 1, 5, and 6 experience travel-time payoffs of -58, -59, and -59, respectively. After the coalition $\{1, 5, 6\}$ forms, those payoffs improve to -52, -52, and -57. Since payoffs are the negative of travel times, each club member arrives sooner. The improvement is not merely collective or average; it is individual for every invited member. This is exactly the kind of deviation that makes club formation credible.

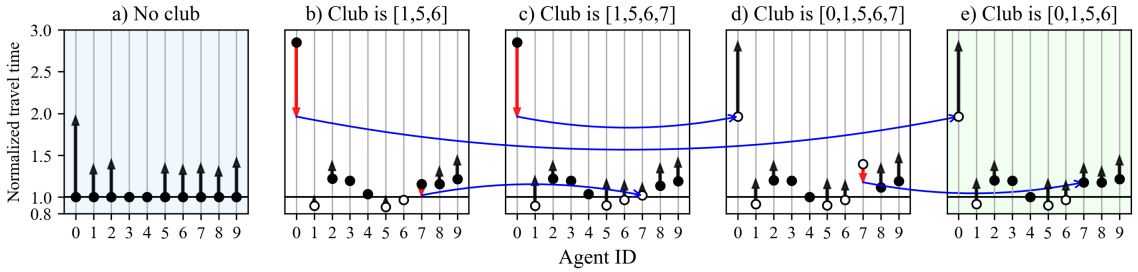


Figure 2: Travel times of 10 CAVs in NE x^0 (a) and in four considered club compositions $\mathbb{1}_{\{1,5,6\}}, \mathbb{1}_{\{1,5,6,7\}}, \mathbb{1}_{\{0,1,5,6,7\}}, \mathbb{1}_{\{0,1,5,6\}}$ (b-e). Travel times are normalized across the 5 plots, such that the travel time of all agents in x^0 is 1. Black (respectively red) arrows show how much time each agent would lose (respectively gain) by changing route unilaterally from a given joint action. The absence of red arrows is therefore equivalent to the joint action being a Nash equilibrium (a) and (e). Club members (deviating to Route 1) are marked with white circles, and those not invited (remaining at Route 0) with black ones. Blue arrows connect cases where an agent can gain time by changing route unilaterally to the state resulting from this change.

$x \in X$	$g_0(x)$	$g_1(x)$	$g_5(x)$	$g_6(x)$	$g_7(x)$	Mean	State
x^0	-27	-58	-59	-59	-51	-48.3	NE
$\mathbb{1}_{\{1,5,6\}}$	-77	-52	-52	-57	-59	-56.6	
$\mathbb{1}_{\{1,5,6,7\}}$	-77	-52	-53	-57	-52	-55.8	
$\mathbb{1}_{\{0,1,5,6,7\}}$	-53	-53	-53	-57	-71	-55.1	
$\mathbb{1}_{\{0,1,5,6\}}$	-53	-53	-53	-57	-60	-54.4	SE

Table 1: Payoffs $g_i(x)$ experienced by respective club members, players i (columns) for joint actions $x \in X$ (rows) of respectively formed clubs ($\mathbb{1}_I$ denotes the joint action $(1_I, 0_{-I}) \in X$ such that all members of I deviate to Route 1 and other agents remain on Route 0. Shaded cells denote club members. The *mean* column reports the average payoff over all 10 AV players, the State column indicates whether the joint action is a Nash equilibrium and/or a strong equilibrium (recall $SE \subset NE$).

The mechanism behind the gain is the interaction between route demand and signal control. By moving several vehicles to Route 1 at once, the coalition changes the adaptive allocation of green time in its favor. The club does not simply discover a permanently underused route; it strategically changes the network supply conditions. In static or purely first-in-first-out environments, such result may not occur.

The consequences for non-members are negative (Fig. 3). The club improves the travel times of those invited to move, but it worsens conditions for travelers who remain on Route 0. Table 1 shows this clearly for vehicle 0, whose payoff deteriorates from -27 in the initial

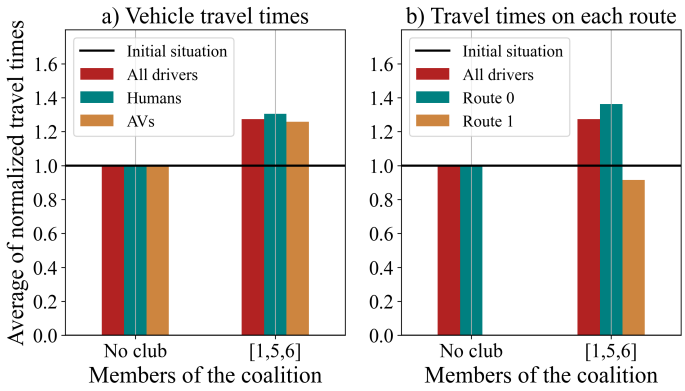


Figure 3: System-wide performance. a) Travel times (payoffs) experienced by various groups of players (humans, AVs, and all) before (left) and after coalition $\{1, 5, 6\}$ is formed (right). b) Average travel times experienced on respective routes. Values normalized to travel times in UE.

equilibrium to -77 once coalition $\{1, 5, 6\}$ forms. More broadly, the average payoff over autonomous vehicles becomes worse after the club forms, indicating a higher mean travel time. The coalition is therefore privately profitable and socially harmful.

Figure 2 shows that: i) the initial profitable coalition can trigger a cascade of unilateral joining behaviour, ii) not every expansion remains stable. The configuration $\{0, 1, 5, 6, 7\}$ becomes internally unstable because one member would prefer to leave once the coalition becomes too large. The final terminal coalition in the graph is $\{0, 1, 5, 6\}$, which we identify as a candidate for a strong-equilibrium (assuming, for now, no adaptations in human behaviour).

Even in this tiny network, the ten autonomous vehicles generate 1024 possible joint actions. We report (Fig. 4) a rich landscape of route-level travel times and equilibrium types across these states. Most joint actions are not Nash equilibria, some states admit club formation, and only one strong equilibrium is identified in the presented analysis. This indicates that mixed-autonomy route-choice games with adaptive control can produce strategically complex outcome sets even in minimal settings.

4 Conclusions

This paper demonstrates that route-choice equilibria in mixed traffic may cease to be strong once connected autonomous vehicles can coordinate their route choices. In the presented microscopic network, the baseline user equilibrium is stable against unilateral deviations, yet a three-vehicle coalition can jointly switch routes and make every member better off. The coalition does so by altering not just the route split but also the adaptive signal response of the network.

We challenge the sufficiency of classical equilibrium analysis in future road networks. If a subset of travelers can coordinate their route choices through a common platform, the assumption of purely individual deviations becomes restrictive. Standard traffic assignment may therefore underestimate both the strategic leverage of fleet operators and the possibility that route guidance systems create private rather than public benefits.

The results open a new regulatory concern. Adaptive traffic control and public-road capacity are collective resources. If CAV operators can exploit those responsive systems to improve payoffs for selected users, then road-space governance may need to address not only congestion and safety, but also access to coordination. That could imply new rules for routing platforms, signal-control interaction, or fairness constraints in connected mobility services.

Nonetheless, this study should be interpreted as an existence proof rather than a universal

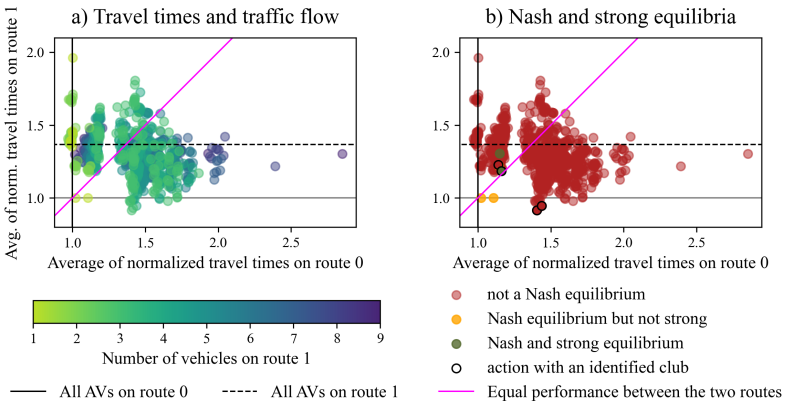


Figure 4: **System states across various joint actions.** Each dot denotes a joint action and its coordinates are the average travel times on Route 0 (x-axis) and Route 1 (y-axis), normalized such that the travel time of all vehicles in x^0 is 1. The pink diagonal represents equal travel times on both routes. On panel a) dots are colored proportionally to the split of vehicles between routes. On panel b), colors denote various equilibrium states: red when it is not Nash (with a black circle when clubs were identified), yellow for Nash, and green for strong Nash. We identified several joint actions where we can identify a club (bold circles on b); however, most of the joint actions were not in Nash Equilibrium (red), and only one action was Strong Nash (green).

prediction. We do not claim that every adaptive-control network will generate harmful clubs, nor that any amount of coordination is socially undesirable. It, for the first time, shows that under plausible conditions the mechanism can emerge, and that the resulting outcomes can be both inequitable and inefficient. Establishing that possibility is already important, because it expands the design space that transportation researchers and regulators must consider.

Acknowledgements

This research is financed by the European Union within the Horizon Europe Framework Programme, ERC Starting Grant number 101075838: COeXISTENCE.

References

Aumann, R. J. (1959). Acceptable points in general cooperative n-person games. In A. W. Tucker & R. D. Luce (Eds.), *Contributions to the theory of games iv* (pp. 287–324). Princeton, N.J.: Princeton University Press.

Bernheim, B., Peleg, B., & Whinston, M. D. (1987). Coalition-proof nash equilibria i. concepts. *Journal of Economic Theory*, *42*(1), 1-12. Retrieved from `https://www.sciencedirect.com/science/article/pii/0022053187900998` doi: https://doi.org/10.1016/0022-0531(87)90099-8

Gartner, N. H., Assmann, S. F., Lasaga, F., & Hou, D. L. (1991). A multi-band approach to arterial traffic signal optimization. *Transportation Research Part B: Methodological*, *25*(1), 55–74. doi: 10.1016/0191-2615(91)90013-9

Lopez, P. A., Behrisch, M., Bieker-Walz, L., Erdmann, J., Flötteröd, Y.-P., Hilbrich, R., ... Wießner, E. (2018). Microscopic traffic simulation using SUMO. In *The 21st ieee international conference on intelligent transportation systems*. IEEE. Retrieved from `https://elib.dlr.de/124092/`

Nash, J. F. (1950). Equilibrium points in n-person games. *Proceedings of the National Academy of Sciences of the United States of America*, *36*(1), 48–49. doi: 10.1073/pnas.36.1.48

Papadimitriou, C. (2001). Algorithms, games, and the internet. In *Proceedings of the thirty-third annual acm symposium on theory of computing* (p. 749–753). New York, NY, USA: Association for Computing Machinery. Retrieved from `https://doi.org/10.1145/380752.380883` doi: 10.1145/380752.380883

Pigou, A. C. (1920). *The economics of welfare* (1st ed.). London: Macmillan and Co.

Roughgarden, T. (2007, 01). Routing games. *Algorithmic Game Theory*.

Smith, M. J. (1979). Traffic control and route-choice; a simple example. *Transportation Research Part B: Methodological*, *13*(4), 289–294. doi: 10.1016/0191-2615(79)90021-3

Varaiya, P. (2013). Max pressure control of a network of signalized intersections. *Transportation Research Part C: Emerging Technologies*, *36*, 177–195. doi: 10.1016/j.trc.2013.08.014

Wardrop, J. G. (1952, May). Road paper. some theoretical aspects of road traffic research. *Proceedings of the Institution of Civil Engineers*, *1*(3), 325–362. Retrieved from `http://dx.doi.org/10.1680/ipeds.1952.11259` doi: 10.1680/ipeds.1952.11259