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Pedestrians, Autonomous Vehicles, and Cities

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Abstract

Autonomous vehicles, popularly known as self-driving cars, have the potential to transform travel behavior. However, existing analyses have ignored strategic interactions with other road users. In this article, I use game theory to analyze the interactions between pedestrians and autonomous vehicles, with a focus on yielding at crosswalks. Because autonomous vehicles will be risk-averse, the model suggests that pedestrians will be able to behave with impunity, and autonomous vehicles may facilitate a shift toward pedestrian-oriented urban neighborhoods. At the same time, autonomous vehicle adoption may be hampered by their strategic disadvantage that slows them down in urban traffic.

Keywords

autonomous vehicles, self-driving cars, pedestrians, crosswalks, game theory, transportation, urban form

Introduction

Pedestrians routinely play the game of chicken. Crossing the street, even at a marked although unsignalized crosswalk, requires an implicit, instantaneous probability calculation: what are the odds of survival? The benefit of crossing the street more quickly, rather than taking a long detour or waiting for a gap in traffic, is traded off against the probability of injury or even death.

Pedestrians know that drivers typically have no interest in running them down. So why not simply step out into the street and assert the right of way? In part, because they also know that there is a small probability that the driver is inattentive, intoxicated, or sociopathic, or that the vehicle may be unable to stop in time. Moreover, because local norms typically dictate that pedestrians wait for cars to pass, drivers do not expect them to cross, amplifying the risk. In most cities, this tiny risk of injury or death keeps pedestrians firmly on the sidewalk, children (and dogs) on a short leash, and traffic flowing smoothly. In particular contexts such as college towns, in contrast, the norms are reversed; drivers adjust to the unpredictability of pedestrians, and modify their speed and behavior accordingly.

In this paper, I use game theory to develop a new model of road user interactions that formalizes this game of "crosswalk chicken" between pedestrians and drivers. I then use this model to draw out the implications for autonomous vehicles, popularly known as self-driving cars.[1] Autonomous vehicles could provide the most dramatic transformation in urban transportation systems, and the largest upheaval for transportation planning practice, since the arrival of the motor car more than a century ago. Parking provision, street design, and transit and paratransit service networks are likely to be revolutionized. However, the strategic implications for other road users have so far been ignored.

At face value, autonomous vehicles promise a future where drivers are freed from a tedious chore and traffic collisions are a relic of history. The game theoretic analysis presented here suggests an alternative scenario, where increased adoption of autonomous vehicles renders their desirability, from the perspective of the driver, questionable in many urban environments. Instead, pedestrian travel becomes quicker, safer, and more attractive, and human-driven vehicles may be faster than their autonomous counterparts.

What causes this paradox? The answer lies in a likely hallmark of autonomous vehicles—their safety. Given a risky situation, the autonomous car slows down and yields. Even at midblock and unmarked crosswalks,[2] the cars—programmed to obey the rules of the road—wait for pedestrians to cross. In turn, safer cars provoke a rational response by pedestrians and other road users. Secure in the knowledge that a car will yield, pedestrians can cross with impunity. They merely need to act unpredictably or step into the street to force the risk-averse car to slow down. From the point of

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view of a passenger in an automated car, it would be like driving down a street filled with unaccompanied five-year-old children.

In this article, I examine one situation in detail—yielding of pedestrians and drivers at uncontrolled crosswalks. The broader contribution of this article, however, is to highlight the changes in strategic incentives that would accompany the widespread adoption of autonomous vehicles. For example, autonomous vehicles could empower cyclists to "take the lane" and ride on streets without dedicated bicycle lanes or other infrastructure. Jaywalking could also become more prevalent, and parents may feel more confident in allowing children to play on residential streets. In short, pedestrians and other humans could actively exploit the predictable and safe behavior of autonomous vehicles.

I begin with a brief review of the research on the potential impacts of autonomous vehicles on travel demand and urban form. I then introduce the "crosswalk chicken" game, and situate it in existing research on pedestrian and driver yielding. The subsequent section and the conclusion bring these two strands together, and analyze some new implications of autonomous vehicles for planning practice and urban policy.

Autonomous Vehicles, Travel Demand, and Safety

Autonomous vehicles bring immense potential to radically alter both the structure of cities and the dynamics of transportation systems. Assistive technologies such as lane-keeping and adaptive cruise control are already available in new vehicle models, and the coming years are likely to see a gradual shift toward autonomy. Levinson and Krizek (2015, chap. 7) suggest that full automation might be required in all new vehicles in the United States by 2030, and that "human drivers will eventually be prohibited on public roads."

There is considerable scope for autonomous vehicles to reduce energy consumption per mile driven (Wadud, MacKenzie, and Leiby 2016). Most analysts also suggest that autonomous vehicles would bring large gains in road safety. Autonomous vehicles can more effectively sense the presence of other road users and predict their behavior, and do not become intoxicated or fall asleep at the wheel. This does not mean that vehicle collisions will be eliminated, with crashes involving Tesla's "autopilot" feature attracting particular media attention (Lee 2016), but rather that in aggregate they will become far fewer.

Predictions of the travel demand impacts of autonomous vehicles, in contrast, are more varied. Research in this area has, by necessity, been largely theoretical, verging on the speculative. Planning practice is in a similar position, and uncertainty about the timing and impacts of autonomous vehicles has hampered planning for their arrival (Guerra 2016).

Predictions of the implications for travel behavior and urban form fall into two broad schools of thought (Fagnant and Kockelman 2015; Heinrichs and Cyganski 2015; for comprehensive discussions, see Levinson and Krizek 2015; Milakis, van Arem, and van Wee 2015; Guerra 2016; Wadud, MacKenzie, and Leiby 2016). The first school emphasizes the potential of autonomous vehicles to stimulate additional travel. With no need for a driver, vehicle occupants would be free to engage in other activities during the trip, in turn reducing the time costs of travel and facilitating urban sprawl. Autonomous vehicles could enable the young and people with disabilities to travel more easily by private car. By functioning as a low-cost, driverless taxi, they could also attract trips away from public transit and nonmotorized modes and increase deadheading. Moreover, autonomous vehicles might induce demand by expanding the capacity of roads, because lanes could be narrowed and cars could follow each other more closely.

Another school of thought emphasizes the potential for autonomous vehicles to reduce vehicle travel. In part, this might come through a shift away from private car ownership and toward "mobility as a service" (Levinson and Krizek 2015). Through replacing the fixed costs of car ownership with time- and mileage-based charges for access to a fleet of shared, autonomous vehicles, the marginal cost of each car trip would increase and vehicle travel would fall as a consequence. Moreover, since autonomous vehicles would not require a parking space close to their destination, they could enable denser development and infill on former parking lots (Zhang et al. 2015) and reduce cruising for parking.

Neither of these schools of thought, however, has considered how the likely safety benefits of autonomous vehicles might fundamentally change the strategic interactions between road users. These strategic interactions are considered formally in the following section.

The Crosswalk Chicken Game

In the game of chicken, two drivers begin to drive head-on toward each other at high speed. The winner: the driver who does not "chicken out" and swerve out of the way. The worst possible outcome is that neither driver swerves, and both die as the vehicles collide. Thus, in equilibrium, one driver will chicken out, as losing the game is preferable to death.

Table 1 illustrates the chicken game in a formal game theoretic structure. Each driver receives a payoff of −10,000 for crashing, 0 for swerving, and +100 for winning. There are two possible Nash equilibria—either one driver swerves, or

Table 1. Payoff Matrix for Chicken.

		Driver 1	
		Swerve	Don't Swerve
Driver 2	Swerve	0, 0	100, 0
	Don't swerve	0, 100	−10000, −10000

Note: The payoff for Driver 1 is given first.

Table 2. Payoff Matrix for the Crosswalk Chicken Game.

		Pedestrian	
		Don't walk	Walk
Driver	Yield	0, 0	100, 0
	Don't yield	0, 100	−100000, −1000

Note: The payoff for the pedestrian is given first.

the other does. In these equilibria, neither driver can unilaterally exercise a different option that will leave them better off (for a more general discussion, see Schelling 1956; Colman 2013, 111–15).

A similar setup—the crosswalk chicken game—can be used to analyze the interactions between different road users. Take, for example, an uncontrolled crosswalk, where although the driver usually has a legal duty to yield, enforcement is typically minimal. A pedestrian wishes to cross as soon as possible, and prefers that the driver yield. The driver prefers to avoid stopping. A collision, however, represents the worst outcome for both sides. Admittedly, the collision will leave the pedestrian much worse off, but the delays, financial costs, legal ramifications, and moral guilt inflicted on the driver are far from costless.

Table 2 represents these payoffs in the same formal game theoretic structure as Table 1.[3] The payoff of −100,000 to the pedestrian in the event of a collision can be interpreted as the probability-weighted costs of varying degrees of injury or death. Just as in the regular chicken game, there are two possible Nash equilibria—Walk/Yield or Don't Walk/Don't Yield. In these equilibria, neither the pedestrian nor the driver can unilaterally exercise a different option that will leave them better off.

The crosswalk chicken game may appear to be narrow in scope, focusing only on delay and the possibility of a collision. The payoffs in Table 2, however, can be thought of as capturing any other costs and benefits in the decisions to yield or walk, respectively, such as the risk of a traffic citation, or altruistic satisfaction gained from letting the other road user proceed first. Provided these are small relative to the costs of delay or collision, the equilibria remain the same.[4] Road user interactions involve a complex blend of physical design, psychology, social norms, and other factors (see, e.g., Vanderbilt 2008), but the game theoretic framework provides analytic traction by distilling many of these considerations down to a single consideration, namely, generalized cost.

Which of the two possible equilibria is chosen? In theory, either result is possible, but in practice, it depends on local social norms. In Manhattan, pedestrians assert their right-of-way with vigor. In most of the rest of the United States, it would be a foolhardy person that steps out into an uncontrolled crosswalk, and the legal requirement for drivers to yield is routinely violated (Schneider and Sanders 2015).[5]

A general principle, however, is that the level of commitment to a given behavior matters. Some road users can more easily change their behavior at the last minute. At an uncontrolled crosswalk with short sight distances, for example, a driver may already be committed to the strategy of "don't yield" by the time she sees the pedestrian. Since the pedestrian knows that the driver cannot stop in time, he chooses the strategy of "don't walk." The analogy in the standard chicken game is a driver who rips off her steering wheel and thereby commits to "don't swerve." As in any bargaining game, being able to constrain one's options can improve one's payoff. Schelling (1956, 306) identifies the "paradox" that "in bargaining . . . to burn bridges behind one may suffice to undo an opponent."[6]

The implication is that the equilibrium where the driver yields is much more likely in places with low speeds; on streets with many children, cows, or other erratic road users; and where pedestrians are more assertive or take risks. Indeed, this is borne out by empirical evidence (Van Houten 2011; Salamati et al. 2013; Schneider and Sanders 2015). Harrell (1992), meanwhile, finds that driver yielding increases when a pedestrian holds a cane, possibly because drivers take the cane as an indication that the pedestrian may be unpredictable, visually impaired, or disoriented. "Rather than motivated solely by a desire to help the pedestrian, the motorist may be protecting himself or herself from precipitous pedestrian behavior that can cause an accident" (Harrell 1992, 352).

Enter Autonomous Vehicles

The model of road user behavior presented above applies to human decisions. Autonomous vehicles are likely to respond very differently, because they are fundamentally unable to win the game of chicken. Moreover, they are likely to obey the rules of the road far more than human drivers, particularly in safety-critical situations. This section elaborates the reasoning.

Consider the game of "crosswalk chicken" in Table 2. In an encounter with a human driver, a pedestrian choosing to walk runs a large risk in a context where the norm is for drivers not to yield. The driver might not be concentrating, might not see the pedestrian, or might not believe that the pedestrian would really step out and cross.

There is almost no risk, in contrast, for the pedestrian to cross in front of an autonomous vehicle, assuming that sight distances and speeds provide sufficient braking distance. The pedestrian knows that the autonomous vehicle will stop. The pedestrian knows that the autonomous vehicle will not be drunk or distracted. And the pedestrian knows that the autonomous vehicle will follow the law.

There is considerable evidence that autonomous vehicles drive much more cautiously than the majority of human drivers. Almost all of the reported collisions involving Google's autonomous vehicles have seen it hit from behind, often by a driver that was surprised when the Google vehicle stopped for a pedestrian or otherwise followed the rules (Richtel and Dougherty 2015). "We make the cars as paranoid as possible, because there are some things they won't be able to avoid," says Google's project lead for self-driving cars (quoted in Rogers 2016).

Autonomous vehicles may also be more law abiding. In all US states and Canadian provinces, the pedestrian normally has the legal right-of-way in law in a crosswalk, even if that crosswalk is unmarked (Schneider and Sanders 2015). While this legal reality is often ignored by human drivers, an autonomous vehicle would likely be programmed to respect the pedestrian's right of way. The consequences of an alternative choice would be far too severe for the vehicle manufacturer or software developer, given the risk of punitive damages or criminal proceedings in the event of a collision. Even if autonomous vehicles rely on adaptive learning algorithms, these would still be likely to be risk-averse and to respect traffic laws. Moreover, unlike a human driver, an autonomous vehicle could not claim that it was distracted and did not "see" the pedestrian. Assuming the existence of a "black box"–style recorder, the data would show otherwise.

The revelation in 2015 that Volkswagen programmed its cars to evade emissions tests provoked public outrage and tens of billions of dollars in probable liabilities. Imagine the consequences if its cars had been programmed, in effect, to hit law-abiding pedestrians. While the overall situation with legal liability for collisions involving autonomous vehicles is unclear, vehicle manufacturers are likely to assume greater liability even in the absence of negligent or reckless behavior (Marchant and Lindor 2012). Meanwhile, several companies such as Google and Volvo have voluntarily pledged to assume liability for collisions involving their autonomous vehicles (BBC News 2015).

The strategic nature of the interactions between road users gives pedestrians a further, distinct advantage in an encounter with autonomous vehicles. In the standard game of chicken, a good strategy is to behave as a sociopath—one who prefers death to losing, and who will not swerve under any circumstances. Visibly ripping off one's steering wheel is a sensible option. Autonomous vehicles are incapable of such behavior, and cannot credibly pretend to be sociopathic. Pedestrians and other human road users, in contrast, gain incentives to behave erratically, even where they do not have the legal right of way. The more it seems that a bicyclist will run a stop sign, a pedestrian step into the road, or a human driver ignore a red light, the more cautiously an autonomous vehicle will behave. Pedestrians gain an incentive to pretend to be drunk, or to ostentatiously behave as if they had no conception that cars could be dangerous.

This model assumes that pedestrians can recognize autonomous vehicles, or that there are sufficiently few human drivers in the mix to prevent the equilibrium in the crosswalk chicken game from shifting to "Walk, Yield." In reality, autonomous vehicles will penetrate the fleet gradually, and will have a variety of appearances that may not be easily recognizable. What, then, is the pedestrian to do, in the face of uncertainty over the type of vehicle being encountered? One option is to step cautiously out into the crosswalk. An autonomous vehicle will likely slow given the uncertainty over the pedestrian's intentions, while a human driver is more likely to maintain his or her speed. (This behavior would also allow the pedestrian to confirm that the autonomous vehicle detection systems have "seen" him or her.) With just a handful of autonomous vehicles in the fleet, it is hardly worth the effort for a pedestrian to gauge the vehicle type by stepping out in this way, but the returns from doing so increase as autonomous vehicles become more prevalent. Over a critical threshold, autonomous vehicles may even shift the equilibrium for human drivers to "Walk, Yield," as pedestrians come to expect any car to stop at the crosswalk.

Planning and Policy Scenarios

The planning and policy implications of autonomous vehicles are potentially wide-ranging, influencing issues from parking provision to mobility for people with disabilities. Consideration of the strategic interactions between autonomous vehicles and other road users adds a further dimension to the uncertainty, with particular implications for the physical design of urban neighborhoods.

Since the late 20th century, planning practice in the United States and Europe has increasingly frowned upon the segregation of road users in many contexts. For example, the construction of urban freeways and expressways has slowed, and some have been demolished (DiMento and Ellis 2013, 220–29). Instead, many planners are moving toward street designs that rely on visual and social interactions between different road users, and mediate conflicts through norms and deliberate uncertainty rather than physical barriers and legal rules. Planners and researchers are also increasingly emphasizing the importance of streets as places of social interaction and recreation (Southworth and Ben-Joseph 2003; Gehl 2011). At the extreme, "living streets" or "woonerfs" offer no distinction between the sidewalk and roadway, and all road users share the same space. Common in the Netherlands, such designs are beginning to appear in the United States and other countries (NACTO 2013; Karndacharuk, Wilson, and Dunn 2014).

In low-volume settings such as suburban residential neighborhoods, autonomous vehicles may well reinforce and facilitate these trends—and provide planners with the opportunity to promote shared-use designs. It becomes more appealing to stroll along a shared street, or allow one's children to play outside, safe in the knowledge that autonomous vehicles will obey traffic regulations, and slow down and yield if necessary for safety.

In denser, urban settings, in contrast, where competition for street space is intense, the strategic interactions between road users may limit the benefits of autonomous vehicles.

Their greater propensity to follow traffic regulations may put autonomous vehicles at a disadvantage, even before pedestrians respond strategically to their law-abiding behavior. And once pedestrians, cyclists and human drivers learn to exploit the caution of autonomous vehicles, the speed of driving through a city will be further hampered.

The ultimate impacts of autonomous vehicles on travel and the built environment are still speculative. However, the game theoretic analysis here suggests several new possibilities.

Pedestrian Supremacy

The first scenario envisages urban environments where pedestrians, and perhaps bicycles, dominate. Pedestrians know that autonomous vehicles will behave cautiously in their presence, which generates a self-reinforcing process. Pedestrian activity slows down autonomous vehicles, especially on non-arterial streets, which in turn makes walking a quicker alternative for more trips. Because it is difficult for autonomous vehicles to penetrate the heart of urban neighborhoods, they tend to drop off their occupants on an arterial road at the edge, before heading to a peripheral parking facility. This enables further increase in urban density, which again contributes to higher pedestrian activity.

Regulatory Response

In this scenario, policy makers react to the impunity shown by pedestrians with a combination of regulatory changes, physical design, and enforcement. Laws are changed to reduce pedestrian priority, for example, by eliminating unmarked crosswalks at intersections. Physical barriers in the form of fences between the sidewalk and roadway are erected to corral pedestrian traffic along busy streets, marking a return to the mid-20th century street designs that emphasize segregation of road users. Enforcement action against jaywalkers and similar violators is stepped up, and legislation specifies that an autonomous vehicle manufacturer is not liable for any collision where a pedestrian was unlawfully present in the roadway.

Human Drivers

The implicit assumption of much analysis of autonomous vehicles is that travelers would prefer them to a human-driven car, at least if the cost were similar. However, this may not be the case should autonomous vehicles prove to be slower than a human-driven alternative. Even on main arterials and freeways, autonomous vehicles may be slower if, in contrast to humans, they respect speed limits. In urban environments, the speed differential may be greater, partly because minor infringements of traffic rules confer a greater speed advantage, and partly because human drivers can be less cautious in the presence of pedestrians. Human drivers retain the credible threat that they will collide with a jaywalking pedestrian, giving them a strategic advantage in the “crosswalk chicken” game. Some travelers may trade the benefits of autonomous vehicles, such as the freedom to engage in other activities during the trip, for the speed advantage of human driving.

These three scenarios may well be precluded by regulation, taxation, or other policy or physical street-design changes. Hybrid scenarios are also possible. The point here is not that one scenario will necessarily prevail, but that the challenges can be analyzed in the strategic interactions of a game theoretic model.

Moreover, the impacts of autonomous vehicles will depend not just on technological progress, but also the legal, policy and urban planning response. If decision makers wish to capitalize on the potential of autonomous vehicles to create more livable, walkable urban places, one approach would be to promote ambiguity in street design through shared-space concepts such as the woonerf (Karndacharuk, Wilson, and Dunn 2014). Designs that give pedestrians the confidence—and legal priority—to enter the roadway become more feasible if many or most vehicles are autonomous. Alternatively, planners could develop a more explicit typology of streets, consisting of (i) streets for motor vehicles, where pedestrian movement is constrained by physical barriers or greater enforcement; and (ii) streets for non-motorized users, where cars proceed slowly and yield to pedestrians. Such an explicit division of street function might be necessary to maintain access (for both private cars and public transit) to the dense urban cores, while maintaining the vitality and appeal of such urban places.

More broadly, this paper highlights the insights that arise from analyzing the strategic incentives created by autonomous vehicles. Most writing on the subject has implicitly assumed that autonomous vehicles will “play nice” and cooperate with each other. But this assumption may not match optimal private behavior, and instead, autonomous vehicles may create new collective action problems. Traffic congestion could be worsened if autonomous vehicles cut in front of each other with impunity, safe in the knowledge that the other car will yield and brake. The vehicles of a particular manufacturer could cooperate with each other to reduce their collective travel times at the expense of other road users. (A Honda might cut off a Toyota, but not another Honda.) Or consider the Super Bowl scenario,[7] where each spectator exiting the stadium wants to be picked up by his or her own autonomous vehicle, and instructs the vehicle to time its arrival at the curb to minimize the waiting time for its intended occupants. To achieve this, one option would be to circle the block, creeping slowly along the final block at the minimum possible speed in the hopes that its owner would emerge. For one vehicle to do this would be annoying. Imagine the gridlock should all seventy thousand Super Bowl attendees do the same.

Fundamentally, the rules of the road are social. Laws provide a framework, but norms develop on top of legal and institutional incentives, leaving laws as a starting point rather than a complete guide to road user behavior. A benign vision of autonomous vehicles implies cooperative behavior, but at least a minority of road users may seize the advantage from pursuing a selfish strategy. Technological problems will almost certainly be resolved by continued research and development. The disadvantages that autonomous vehicles face in their strategic interactions with human road users, on the other hand, are intrinsic.

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Notes

1. Autonomy is a spectrum, ranging from assistive features such as automatic braking, to full automation. I focus on Level 4 automation according to the National Highway Traffic Safety Administration classification, under which the driver completely relinquishes control.
2. Under the traffic and vehicle codes of nearly all US states, crosswalks are presumed to exist at an intersection, whether they are marked or not. Hence, the existence of "unmarked crosswalks."
3. The game theoretic model is similar to that in Chen, Wu, and Zhu (2016) and Bjørnskau (2015), although there are key differences. Chen et al. empirically estimate when pedestrians choose to cross, and do not explore the strategic incentives that I discuss below. Bjørnskau's "zebra crossing game," meanwhile, involves a cyclist deciding whether or not to dismount before using a crosswalk.
4. The same insights also arise from a more complex model that treats the encounter as a continuous process, whereby the pedestrian edges out to ascertain the driver's intention, or the driver honks the horn. These additional steps may add to the stress of the encounter, but otherwise do not change the payoffs. In general, if one knows that one is going to have to yield, one should cede the right-of-way early on, in order to avoid the discomfort and stress of sudden braking or taking evasive action. Similarly, the model can be made more complex through adding multiple road users, such as several pedestrians or vehicles, or a bicycle in an adjacent lane, but the core insights remain the same. A similar point applies to a game theoretic model (e.g., a Bayesian game) that invokes the beliefs of pedestrians or drivers about whether the other road user will yield.
5. The "don't walk, don't yield" outcome could also be predicted as a "trembling hand perfect" equilibrium, which acknowledges the potential for the car or pedestrian to choose an unintended strategy. Because the consequences of a collision are greater for the pedestrian than the driver, the risk that the driver will fail to yield implies that the "don't walk/don't yield" equilibrium will be more common except in low-speed environments. More generally, more complex game theoretic concepts could be applied to road-user interactions, which may be useful in a traffic simulation or similar model, but would obscure the central insights in this paper.
6. Schelling (1956, 294) gives a related example of how constraining one's behavior improves one's payoff: "If one driver speeds up so that he cannot stop, and the other realizes it, the latter has to yield."
7. Or the opera scenario, depending on one's cultural preferences. A version of this behavior was evident at airport terminals before the advent of cellphone lots (Kramer and Mandel 2015).

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