ALL-WAY STOPS

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Abstract

We show that tweaking a familiar crossroad-traffic-control practice in the United States has the potential to significantly reduce energy consumption and carbon emissions (more than one week of gas consumption every year) while NOT jeopardizing road safety: Instead of erecting one stop sign in each direction (e.g. four stop signs at a four-way crossroads), erect one fewer sign at each crossroads (e.g. only three stop signs at a four-way crossroads). The simpler mechanism preserves road safety because it permits all drivers' abidance of traffic rules as a Nash equilibrium, while the existing mechanism does not. Hence, the new mechanism is also self-enforcing, leading to savings in police expenditures besides those in carbon/pollutants emissions, drivers' time, and infrastructure costs.

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In the United States and many other countries, at crossroads without traffic lights, a common mechanism for resolving the conflict between vehicles moving in intersecting directions is to erect one stop sign in each direction (e.g., the intersection of two roads with bidirectional traffic will have four stop signs in total). Then the traffic rules accompanying the existing mechanism stipulate the following: Vehicles approaching from all directions are required to stop at their respective signs and pay attention to the traffic coming from other directions; When multiple vehicles arrive at the crossroads, the right-of-way gives to the one that arrives at the crossroads the earliest, and all vehicles pass the crossroads sequentially. When all drivers abide by the traffic rule, this mechanism ensures orderly passing and avoids collisions.

The existing mechanism is so widely adopted that few people ever doubt whether it is efficient — except that it is not.[1] Furthermore, this mechanism is not even incentive compatible. Intuitively, assuming that drivers get a disutility from stopping their moving vehicles but they also do want to avoid collisions, then it is not a Nash equilibrium for drivers in all directions to abide by their respective stop signs: As a profitable deviation, if you believe that all other drivers will stop at the crossroads and observe the traffic before moving again, you know that you can avoid collisions even if you just run the stop sign. Then under the usual rationality assumption for economic agents, how can we expect a selfish driver, who does not care about the angry curses from drivers in the other directions, to ever abide by the stop-sign rule at all? Indeed, for crossroads in which every direction has a stop sign, we prove that any Nash equilibrium always features some drivers running the stop sign!

One may argue that drivers abide by the traffic rules not only to avoid collisions but also

[1]It may be argued that when it comes to stop-sign mechanisms, efficiency is a secondary concern compared to safety, as engineering professionals often follow the doctrine of "public welfare and safety above all considerations." As we will make clear in subsequent discussions, we are not against this doctrine, in that we are concerned about efficiency enhancement that does not jeopardize road safety.

to avoid getting (occasionally) caught and ticketed by the police. However, in addition to recognizing that police monitoring over the gigantic number of crossroads is highly imperfect, one may also question why police are really necessary to ensure orderly passing and no collisions in the first place. Indeed, relying on law enforcement to ensure traffic abidance may be a suboptimal mechanism, as it incurs extra police expenses and taxpayer burdens, especially given that self-enforcing mechanisms do exist, as we show below:

Instead of erecting one stop sign in every direction of a crossroads, we consider simply removing one sign — any one, and allowing vehicles in that direction to pass without stopping. We prove that under this new mechanism, it is indeed a Nash equilibrium for all drivers in the remaining directions with stop signs to abide by the traffic rule, as their cost (chance of collision) of running the stop sign increases (which in turn deters them from running the stop sign). In this equilibrium, no police monitoring is ever needed (so police funding could be put in more efficient alternative uses). In addition, at each n-way crossroads (i.e., $n = 4$ at a four-way crossroads and $n = 3$ at a three-way T-crossroads), $\frac{1}{n}$ of the infrastructure costs in erecting/maintaining stop signs could be saved from taxpayers. Furthermore, to the extent that every deceleration/reacceleration at the stop sign leads to additional gas consumption and thus carbon emission,[2] by removing one stop sign, on average $\frac{1}{n}$ of the additional energy use can be saved compared to under the existing all-way-stop-sign mechanism (assuming traffic rule abidance). Similar arguments also go for brake wears.[3]

While the additional savings at each crossroads may be small, given the sheer number of crossroads and the frequency of traffic, the aggregate savings are still significant. For example, we estimate that if we remove one stop sign at each four-way or three-way crossroads, the annual gas savings in the United States amount to over one week of total gas consumption.

[2]Indeed, transportation accounts for 28% of greenhouse gas emissions in the United States. See https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions.

[3]According to Grigoratos and Martini (2015), brake-dust emissions contribute up to 55% by mass to total non-exhaust traffic-related PM10 emissions.

Given the heated contemporary discussions on infrastructure spending, global warming, high energy prices, taxation, police funding, etc.,[4] we think our findings could spur timely discussions with significant economic impacts on the aggregate economy and everyone's daily life. In addition to the above implications, we believe that our results may also have theoretical contributions: While our model is highly stylized, we expect further enrichment and extensions to open new paths of bringing game-theoretical reasoning to transportation problems in specific and operations research in general.

While it may seem absurd to challenge a widely-adopted rule, some facts may speak for themselves: Despite its popularity in many countries such as the United States, Canada, Mexico, South Africa, Liberia, etc., the all-way stop sign mechanism has not been adopted globally. For example, in the United Kingdom, all-way stops have always been very uncommon and were formally prohibited by the Department for Transport in 2002. In Sweden, all-way stops (Flervägsstopp) have been tested since the 1980s but are little used even though permitted. Indeed, few countries in Europe require all vehicles to stop at the crossroad; Neither are US-style stop sign rules widely adopted in Asian countries such as China. Given the international evidence, a formal analytical framework is called for to guide further evaluations of this important topic, and insights from game theory seem helpful for this call.

The rest of the paper is organized as the following: We will first start with four-way crossroads. Section 1 presents the environment and set up a simple stylized model for a four-way crossroad. Section 2 proceeds to analyze the equilibrium under four stop signs. The main result is that all drivers abiding by the stop sign rule do not constitute a Nash equilibrium. This section also discusses the cost of police interventions. Section 3 studies an alternative three-stop-sign mechanism, highlighting that under the new mechanism it is incentive-compatible for all drivers to abide by the traffic rule. Section 4 further points out that results from the previous two sections also extend to three-way (T) crossroads. Section

[4]For an overview on the importance of some of the topics listed, see Stiglitz (2016).

5 estimates the lower-bound aggregate economic gains from removing one stop sign at each crossroads. Section 6 discusses related literature. Section 7 concludes with further remarks and future directions.

1 Setup

This section starts our analysis by presenting the environment for a simple model of a four-way crossroads (we will study three-way crossroads in Section 3). Without loss of generality, we assume that one of the two intersecting roads goes horizontally (east-west) and the other goes vertically (north-south), and we denote E, W, N, and S for vehicles that arrive from the east, west, north, and south. For simplicity, we assume that each direction only has one lane. We will later also discuss three-way (T) crossroads, which are assumed (without loss of generality) to feature directions toward the east (E), west (W), and south (S). In this section, however, we will always refer to crossroads as four-way intersections.

Given our humble goal of inspiring new perspectives, in this short article we restrict attention to a highly stylized simple model: Assume that at any given point of time, with a symmetric probability $0 < \theta \leq 1$ there is a vehicle arriving from one of the four directions (E, W, N, and S). Conditional on a vehicle arriving, it has equal probabilities ($\frac{1}{3}$) to turn left, right, or go straight. At the crossroads, drivers may choose to either stop or drive through without stopping to maximize their individual utilities: Each driver derives a small benefit $u > 0$ from an undisrupted driving experience (from say not having to decelerate, stop, and re-accelerate), incurs a tiny additional cost $-c < 0$ (including e.g. gas consumption and thus carbon emissions, break wears, and additional times, etc.), and suffers a huge cost of $-C < 0$ from a collision. Specifically, we assume:

Assumption 1. *The cost of collision is so high that* $\frac{1}{3}\theta C > u + c$.

Assumption 1 is innocuous given that braking/reaccelerating is a minor inconvenience

and its associated extra gas consumption or driving time is infinitesimal. Furthermore, because of the large collision cost of C, drivers try to avoid collisions as long as they can. Specifically, any driver who stops at the crossroads watches the incoming traffic and yields to any non-stopping vehicles to avoid getting into a collision; however, a non-stopping driver cannot quickly respond to traffic conditions, so he will end up in a collision if there is another non-stopping vehicle on a conflicting path.

2 Four stop signs: No traffic-rule-abiding equilibrium

This section proceeds to analyze the equilibrium where there are four stop signs at the crossroads as is commonly observed. We first consider a setting without police and analyze whether the traffic rule associated with four stop signs is self-enforcing. The key insight is that all drivers abiding by the stop sign rule do not constitute a Nash equilibrium.

Theorem 1 (No rule-abiding equilibrium with four stop signs)**.** *With four stop signs at the crossroads, one for each direction (E, W, N, and S), it is not a Nash equilibrium for all drivers to abide by the traffic rule, that is, to stop at their respective stop signs.*

Proof. We prove the theorem by contradiction. Suppose traffic rule abiding is indeed an equilibrium, then it is a profitable deviation for any one driver to run the stop sign. This is because in the hypothesized equilibrium, believing that drivers in other directions will all abide by the traffic rule and yield to any non-stopping driver to avoid collision, the deviating driver enjoys an undisrupted driving experience and saves on gas/time without the danger of collisions, leading to a net gain of $u + c$. □

Theorem 1 shows that the existing four-sign mechanism is not self-enforcing, so its well-functioning in the long-run requires external interventions such as police monitoring. However, such interventions are not free (and not cheap either), as the next remark goes.

Introducing the police With additional costs, we can allow the police to fine any stop sign violations. Suppose a stop sign ticket costs $T > 0$ and a violation is caught with probability $\delta \in [0, 1]$, then the introduction of police effectively changes drivers' incentive compatibility constraints by replacing u with $u - \delta T$. Apparently, for a given ticket price, a higher monitoring intensity δ induces lower offenses, and an adequately high δT (e.g. if $\delta T > u + c$) may eliminate violations. However, enhancing the police force δ could be costly, so one may be interested in more cost-effective ways to mitigate violations. The next section will propose one of such alternative mechanisms that is self-enforcing and thus cost-effective.

3 A new mechanism: Three stop signs

Instead of erecting four stop signs at the crossroads, consider an alternative mechanism: Erect only three stop signs at a four-way crossroads and allow vehicles from an arbitrary one of the four directions to pass the crossroads without having to stop. Theorem 2 below will prove that this new mechanism permits universal traffic-rule abidance as a Nash equilibrium. As a result, the new mechanism is self-enforcing and thus saves on police expenses.

Theorem 2 (Rule-abiding equilibrium with three stop signs)**.** *With three stop signs at the crossroads, one for any three among the four directions (E, W, N, and S), it is a Nash equilibrium for all drivers to abide by the traffic rule, that is, for those who face stop signs to stop (and those who do not face a stop sign to proceed without stopping).*

We delegate the proof to the appendix and merely highlight the intuition behind Theorem 2 here: Knowing that drivers from other directions may not stop at the crossroads, a driver who does face a stop sign would now perceive a non-zero collision probability if he *violates* the stop-sign rule, and thus has stronger incentives to avoid it. In other words, by exempting some drivers from stopping at the crossroads, the three-sign mechanism increases the cost

of traffic rule violations to those who still face stop signs, which in turn deters traffic rule violations as rational responses.

One may question how applicable such game theoretical reasoning is for the specific setting we study — indeed, how can we imagine drivers solving for Nash equilibrium in real-time when on wheels? However, we emphasize that the power of our result lies in the fact that for rule-abiding drivers, the new mechanism requires no changes in behaviors so they can stick to their default driving habits without extra calculation. This is because the new mechanism requires no changes to existing traffic rules: Again, one who faces a stop sign is still required to stop (and has full incentives to do so under the three-sign mechanism), and one who faces no stop sign still can freely pass.

4 Three-way crossroads

While our analysis so far has been motivated by observing four-way crossroads, with an almost unchanged logic, we can obtain similar results as in Theorem 1 and 2 for three-way (T) crossroads as well:

Theorem 3. *With three stop signs a three-way (T) crossroads, one for each direction (E, W, and S), it is not a Nash equilibrium for all drivers to abide by the traffic rule, that is, to stop at their respective stop signs; On the other hand, with two stop signs at a three-way (T) crossroads, one for any two among the three directions (E, W, and S), it is a Nash equilibrium for all drivers to abide by the traffic rule, that is, for those who face stop signs to stop (and those who do not face a stop sign to proceed without stopping).*

Theorem 3 shows that similar to in four-way crossroads, in a three-way (T) crossroads it is also not a Nash equilibrium for everyone to abide by the traffic rule when all directions are saturated by stop signs; By arbitrarily removing one stop sign, however, it becomes incentive compatible for all drivers to abide by the traffic rule. The proof logic is also similar: It is

a profitable deviation for a driver to run the stop sign when believing that all other drivers will stop and watch the traffic, but the cost of such a violation would increase if drivers in some other directions do not stop, which in turn deters traffic rule violations.

5 Aggregate economic implications

Aside from being a self-enforcing mechanism and thus saving police expenditures, it is also immediate that the equilibrium outcome under the new mechanism of removing one arbitrary stop sign saves on infrastructure expenditures (as $\frac{1}{4}$ of all stop signs at four-way crossroads and $\frac{1}{3}$ of all stop signs at three-way crossroads are no longer needed). Furthermore, compared to the policed outcome under mechanisms with saturated stop signs, the new mechanism additionally reduces on average $\frac{1}{4}$ (or $\frac{1}{3}$) of the extra energy consumption/break wear/driving times spent at four-way (or three-way) crossroads from braking at stop signs. Although the incremental savings to each driver from the new mechanism is arguably tiny, the aggregate savings could nevertheless still be significant due to the sheer number of crossroads and amount of traffic.

In this section, we demonstrate the economic implications of removing one stop sign at each crossroads by quantifying the total savings to the aggregate economy. Since our objective is just to show that the economic savings could be significant even based on conservative estimates, we will adopt rough back-of-the-envelope calculations with many simplified assumptions to illustrate orders of magnitudes, rather than going after precise numbers.

Estimating stop counts First, we estimate the number of stops the new mechanism can save. According to Boeing (2020), there are 6,253,254 intersections in the United States (497 urbanized areas $\times$ 12,582 intersection count per urbanized area), out of which 18.7% (59.3%) are four-way (three-way)intersections. Furthermore, according to the U.S. Access Board,

there are about 300,000 intersections with traffic lights.[5] Therefore, given that $(6,253,254 - 300,000) \times 18.7\% = 1,113,258.5$ and $(6,253,254 - 300,000) \times 59.3\% = 3,530,279.6$, we assume at least 1 million four-way (3.5 million three-way) crossroads with stop signs.

We also need to estimate traffic counts at each stop sign. According to the United States Department of Energy, Americans in total drive 3 trillion miles per year.[6] According to the Federal Highway Administration, there are 3.9 million miles of roadways in the United States.[7] Therefore, given that $3 \times 10^{12}/(3.9 \times 10^6) = 769,231$, we assume that each geographic point (and thus every stop sign) has over 760,000 vehicles passing annually. Therefore, assuming perfect abidance, there are in total 1 million times 760,000, or 760 billion deceleration/reacceleration actions due to stop signs at four-way crossroads every year — under a three-sign mechanism, on average one-fourth, or 190 billion such stops could be avoided. Similarly, there are in total 3.5 million times 760,000, or 2.66 trillion deceleration/reacceleration actions due to stop signs at three-way crossroads every year — under a three-sign mechanism, on average one-third, or 887 billion such stops could be avoided.[8]

Estimating energy consumption savings We now use energy consumption as an example to illustrate the order magnitude of savings from our new mechanism. To do so, we need to first estimate the extra gas consumption of each brake/reacceleration. Assume a conservative average vehicle weight of 2 tons and a normal driving speed of 25mph (or

[5] See https://www.access-board.gov/research/prow/interfacing-aps/traffic-signal-controllers-aps-technologies/.

[6] See https://afdc.energy.gov/data/10315.

[7] See https://www.fhwa.dot.gov/ohim/onh00/our_ntns_hwys.pdf.

[8] To ensure the accuracy of this rough estimate, we also consider an alternative counting method: Since the intended use of all-way stops is to enhance overall intersection safety and/or efficiency, such a mechanism is in place only if the traffic volume from minor roads is not too low (otherwise no need for stop signs on the main road) and the overall traffic not too high (otherwise signal controls or roundabout should be used). All-way stops typically have a specific traffic volume range of around 300 vehicles per hour on average over an 8-hour period with considerable volume from minor roads. Under this assumption, $300 \times 8 \times 365 = 876,000$ breaks per year indicate that our solution saves $\frac{1}{4} \times 876,000 \times 10^6 = 219$ billion breaks per year at four-way crossroads. Assuming the same parameter for three-way crossroads, we get a saving of $219 \times 10^9 \times 3.5 \times \frac{4}{3} = 1,022$ billion stops. Hence the total savings from both four-way and three-way crossroads stand at $219 + 1,022 = 1,241$ billion stops, which is slightly higher but at a similar magnitude.

11.176 m/s), the vehicle's kinetic energy is $\frac{1}{2} \times 2 \times 10^3 \times (11.176)^2 = 124.9$ kJ. Therefore, it takes at least 124.9 kJ of total work to bring a vehicle back to normal speed after a full stop. In sum, every stop incurs an additional 124.9 kJ of total work. Assuming an efficient 40% brake-specific fuel consumption (a measure of fuel efficiency), the total energy consumption is $124.9/40\% = 312.25$ kJ. Therefore, the new rule saves $312.25 \times (190 + 887) \times 10^9 = 336.29$ trillion kJ of energy. Given that a liter of gasoline produces 31,536,000 joules,[9] the total saving is $336.29 \times 10^{12}/31,536 = 10.66$ billion liters of gas or about 2.82 billion gallons, which is at the order of 7.6 days of total US gas consumption.[10] As we shoot for underestimates here, the actual saving could be even larger.

6 Related literature

Although this paper's methodology only relies on textbook game theory, its results nevertheless contribute to multiple branches of economics and operations research. First, it demonstrates the power of strategic reasoning for traffic applications, sharing the spirit of Braess (1968) who popularized interest in traffic equilibrium, as well as Vickrey (1969) and Daniel, Gisches and Rapoport (2009), who model drivers' strategic incentives facing traffic bottlenecks. It also provides a new perspective on reducing traffic congestion and improving road safety.[11]

Second, it has the potential to offer an alternative, cost-effective approach to reduc-

[9] See https://energyeducation.ca/encyclopedia/Joule.

[10] We can also estimate savings in total carbon emissions. According to the U.S. Environmental Protection Agency (EPA), every gallon of gasoline burned creates about 8,887 grams of CO_2 (See https://www.epa.gov/greenvehicles/greenhouse-gas-emissions-typical-passenger-vehicle). Therefore, our new mechanism could reduce annual carbon emissions in the United States by $8.887 \times 5.67 = 50$ billion kilograms of CO_2. Since the total annual U.S. greenhouse gas emissions are about 5,981 million tons according to (EPA) (see https://www.epa.gov/climate-indicators/climate-change-indicators-us-greenhouse-gas-emissions), the new rule could reduce the overall (besides traffic-related) US carbon emissions by an order of magnitude of 0.84%.

[11] More economic analyses on traffic congestion include Johnson (1964), Bertrand (1977), Dewees (1979), Duranton and Turner (2011), and Anderson (2014). Those on road safety include Lindgren and Stuart (1980), Dee and Evans (2001), Edlin and Karaca-Mandic (2006), and Anderson and Auffhammer (2014).

ing carbon emission and air pollution,[12] complementing the pricing/trading/tax-based approaches as in Elliott, Foster, Kortum, Munson, Perez Cervantes and Weisbach (2010), Harstad (2012*a*), Golosov, Hassler, Krusell and Tsyvinski (2014), Marron and Toder (2014), Martin, Muûls, De Preux and Wagner (2014), McLure Jr (2014), Acemoglu, Akcigit, Hanley and Kerr (2016), Aghion, Dechezleprêtre, Hemous, Martin and Van Reenen (2016), Lemoine and Rudik (2017),[13] Souza-Rodrigues (2019), Barrage (2020), Iverson and Karp (2021), Reynaert (2021), Van den Bremer and Van der Ploeg (2021), Alexander and Schwandt (forthcoming), and Conte, Desmet and Rossi-Hansberg (2022), vintage-based restrictions as in Barahona, Gallego and Montero (2020), as well as technology- or investment-based approaches as in Chakravorty, Roumasset and Tse (1997), Harstad (2012*b*), and Hassler, Krusell and Olovsson (2021), and adding to the general discussions on emission control (e.g. Nordhaus (2019)). Our potential solution also avoids the leakage problem of direct emission regulations, as discussed in Bushnell and Mansur (2011), Fischer and Fox (2011), Baylis, Fullerton and Karney (2013), Carbone (2013), and Fowlie, Reguant and Ryan (2016).

Finally, our results also contribute to the economics literature on police funding and infrastructure expenses.[14]

7 Conclusion

We point out that for rational drivers who value undisrupted driving experience (but hate collisions), it is not a Nash equilibrium for everyone to follow the traffic rule under the

[12] For estimates on the costs of carbon emission and air pollution, as well as the various costs associated with their reduction, see Stavins (1999), Greenstone (2002), Chay and Greenstone (2003), Currie and Neidell (2005), Walker (2013), Schlenker and W. Walker (2016), Gowrisankaran, Reynolds and Samano (2016), Cai and Lontzek (2019), Cruz and Rossi-Hansberg (2022), and Carleton et al. (forthcoming), etc. Relatedly, Fowlie, Greenstone and Wolfram (2018) estimates the cost of adopting energy-saving technologies.

[13] As well as the comment and reply in Mattauch, Matthews, Millar, Rezai, Solomon and Venmans (2020) and Lemoine and Rudik (2020), respectively.

[14] Specific to traffic enforcement, economic analyses on policing include Makowsky and Stratmann (2009), Eeckhout, Persico and Todd (2010), and Goncalves and Mello (2021). Economic analyses specific to road infrastructures include Thomson (1970), Newbery (1988), and Allen and Arkolakis (forthcoming).

existing all-way-stop mechanism — the resulting outcome is either traffic rule violations or the need for costly police monitoring, neither of which is desirable. We argue that an alternative design, that is, removing one arbitrary stop sign at crossroads that require all-way stops allows traffic rule-abiding behaviors to be a unique Nash equilibrium, and therefore self-enforces without incurring additional policing expenditure. The new design also saves on infrastructure expenses and gas consumption/carbon emission. For example, the annual total national gas consumption savings are estimated to be in the order of one week. In the future, when self-driving cars finally become real, the simpler mechanism may also economize AI computational costs.

We recognize that the validity of any theory ultimately depends on its assumptions. Even though we have established the superiority of one fewer stop sign over all-way stop signs within our rational framework, it remains an empirical question whether any change will have the desired effect in reality, given that drivers may be subject to various behavioral biases. For example, in the presence of "trembling hands," that is, when some drivers may miss stop signs out of negligence rather than strategic calculation, forcing all drivers to stop at the crossroads (and assuming that they will, irrationally, all abide) may allow additional cushions. Therefore, whether any benefits from a three-sign mechanism outweighs its costs need to be empirically tested. Therefore, our paper should not be viewed as an outright recommendation to abolish all-way stop-sign mechanisms and convert them to one-fewer-sign mechanisms, rather it provides a rational benchmark for further evaluations, as a theory typically does.

Since the main purpose of this short article is to challenge conventional wisdom and open new discussions, we have adopted a highly stylized model. Future work may extend our simple framework in multiple directions, for example, allowing asymmetric traffic from different directions (which calls for further investigations to guide which sign to remove), studying multiple-lane roads, and including continuous variables (e.g. how fast one deceler-

ates/reaccelerates, how long one stays at a full stop before reaccelerating, how exhaustive one checks the incoming traffic or how cautious one yield to other drivers) instead of treating abiding traffic rules or not as binary choices, etc. It is also interesting to solve for the optimal mechanism at any crossroads and quantify the maximal cost reduction possible. Further formalization and theorization of our application-motivated analysis may also inspire more advancement in the mechanism design literature.[15] We hope our analysis will serve as a useful example to demonstrate the power of simple game theoretical reasoning for revisiting our everyday transportation experiences and may trigger more follow-up studies to bring economic reasoning to a broader set of management science issues.

[15]See Sandholm (2002) for a mechanism design approach for road congestion pricing.

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Appendix

A All symmetric equilibria under four stop signs

We further characterize all symmetric equilibria (or equilibria hereafter) of the road-crossing game. We follow the United States convention that all vehicles drive on the right side, then Table A1 summarizes all possible scenarios where a collision will take place. For notation ease, we use EW to denote a driver arriving from the east and heading straight to the west, and ES to denote a driver arriving from the east and turning left to head south. All other labels are similarly defined. We use "x" to denote a collision.

	EW	EN	ES	WE	WN	WS	NE	NW	NS	SE	SW	SN
EW					x		x	x	x		x	x
EN					x						x	x
ES				x	x	x	x	x	x		x	x
WE			x				x		x	x	x	x
WN	x	x	x				x		x	x	x	x
WS			x				x		x			
NE	x		x	x	x	x				x	x	x
NW	x		x								x	
NS	x		x	x	x	x					x	
SE				x	x		x					
SW	x	x	x	x	x		x	x	x			
SN	x	x	x	x	x		x					

Table A1: All conflicting paths

In sum, a non-stopping vehicle that turns left has 8 possible scenarios of collision, a non-stopping vehicle that goes straight has 6 possible scenarios of collision, and a non-stopping vehicle that turns right has 3 possible scenarios of collision. This asymmetry is intuitive: In the US system where vehicles drive on the right side of the road, a left turn covers a curve with a larger radius than a right turn and thus gets into conflict with more traffic.

Consider a candidate equilibrium featuring the following strategy profile: A left-turning car runs the stop sign with probability $a_L \in [0,1]$, a non-turning car runs the stop sign with probability $a_N \in [0,1]$, and a right-turning car runs the stop sign with probability $a_R \in [0,1]$. We look for conditions under which this strategy profile indeed constitutes an equilibrium.

Payoffs For a left-turning vehicle, in the candidate equilibrium, the payoff from running the stop sign is

$$u - \left(1 - \left(1 - \frac{a_L + a_R + a_N}{3}\theta\right)^2 \left(1 - \frac{a_L + a_N}{3}\theta\right)\right) C, \tag{1}$$

while the payoff from stopping is $-c$ due to extra gas consumption.

To understand (1), consider a vehicle that arrives from the east and turns left to the south without stopping: it gets to enjoy undisrupted driving with benefit u, and there is no additional benefit or loss if no collision happens, but a cost of $-C$ will be incurred if a collision does happen. To calculate the probability of a collision taking place, notice that: First, the driver can avoid collision with vehicles from the west with probability $1-\frac{a_L+a_R+a_N}{3}\theta$; Second, the driver can avoid collision with vehicles from the north with probability $1-\frac{a_L+a_R+a_N}{3}\theta$; and finally, the driver can avoid collision with vehicles from the south with probability $1-\frac{a_L+a_N}{3}\theta$. Therefore, a collision happens with probability $1-\left(1-\frac{a_L+a_R+a_N}{3}\theta\right)^2\left(1-\frac{a_L+a_N}{3}\theta\right)$. Due to the symmetry of the environment, left-turning vehicles from other directions get the same payoff as in (1).

Similarly, for a straight-going vehicle, in the candidate equilibrium, the payoff from running the stop sign is

$$u - \left(1 - \left(1 - \frac{a_L}{3}\theta\right)\left(1 - \frac{a_L + a_R + a_N}{3}\theta\right)\left(1 - \frac{a_L + a_N}{3}\theta\right)\right) C, \tag{2}$$

while the payoff from stopping is $-c$ due to extra gas consumption.

To understand (2), consider a vehicle that arrives from the east and heads straight to the

west without stopping: it gets to enjoy undisrupted driving with benefit u, and there is no additional benefit or loss if no collision happens, but a cost of $-C$ will be incurred if a collision does happen. To calculate the probability of a collision taking place, notice that: First, the driver can avoid collision with vehicles from the west with probability $1-\frac{a_L}{3}\theta$; Second, the driver can avoid collision with vehicles from the north with probability $1-\frac{a_L+a_R+a_N}{3}\theta$; and finally, the driver can avoid collision with vehicles from the south with probability $1-\frac{a_L+a_N}{3}\theta$. Therefore, a collision happens with probability $1-\left(1-\frac{a_L}{3}\theta\right)\left(1-\frac{a_L+a_R+a_N}{3}\theta\right)\left(1-\frac{a_L+a_N}{3}\theta\right)$. Due to the symmetry of the environment, straight-heading vehicles from other directions get the same payoff as in (2).

Again similarly, for a right-turning vehicle, in the candidate equilibrium, the payoff from running the stop sign is

$$u-\left(1-\left(1-\frac{a_L}{3}\theta\right)\left(1-\frac{a_L+a_N}{3}\theta\right)\right)C, \tag{3}$$

while the payoff from stopping is $-c$ due to extra gas consumption.

To understand (3), consider a vehicle that arrives from the east and turns right to the north without stopping: it gets to enjoy undisrupted driving with benefit u, and there is no additional benefit or loss if no collision happens, but a cost of $-C$ will be incurred if a collision does happen. To calculate the probability of a collision taking place, notice that: First, the driver can avoid collision with vehicles from the west with probability $1-\frac{a_L}{3}\theta$; Second, the right-turning driver never collides with vehicles from the north; and finally, the driver can avoid collision with vehicles from the south with probability $1-\frac{a_L+a_N}{3}\theta$. Therefore, a collision happens with probability $1-\left(1-\frac{a_L}{3}\theta\right)\left(1-\frac{a_L+a_N}{3}\theta\right)$. Due to the symmetry of the environment, right-turning vehicles from other directions get the same payoff as in (3).

For a strategy profile (a_L, a_R, a_N) to constitute a Nash equilibrium, we must have the

following three incentive compatibility constraints to be satisfied:

$$\begin{cases} a_L = 1, \text{ if } (1) > -c \\ a_L \in [0,1], \text{ if } (1) = -c \\ a_L = 0, \text{ if } (1) < -c \end{cases}, \quad \begin{cases} a_N = 1, \text{ if } (2) > -c \\ a_N \in [0,1], \text{ if } (2) = -c \\ a_N = 0, \text{ if } (2) < -c \end{cases}, \quad \text{and} \quad \begin{cases} a_R = 1, \text{ if } (3) > -c \\ a_R \in [0,1], \text{ if } (3) = -c \\ a_R = 0, \text{ if } (3) < -c \end{cases}.$$

We can then solve for all symmetric equilibria as summarized below:

Theorem A1 (Equilibria under four stop signs)**.** *Having four stop signs in each direction of a four-way crossroads leads to a unique symmetric equilibrium:* $(a_L = 0, a_N = 0, a_R = 1)$

Proof. Notice that $(1) \leq (2) \leq (3)$, we thus have $a_L \leq a_N \leq a_R$. Therefore, there are ten possible scenarios:

1. $(a_L = 0, a_N = 0, a_R = 0)$ and $((1) < -c, (2) < -c, (3) < -c)$
2. $(a_L = 0, a_N = 0, a_R \in [0,1])$ and $((1) < -c, (2) < -c, (3) = -c)$
3. $(a_L = 0, a_N = 0, a_R = 1)$ and $((1) < -c, (2) < -c, (3) > -c)$
4. $(a_L = 0, a_N \in [0,1], a_R \in [0,1])$ and $((1) < -c, (2) = -c, (3) = -c)$
5. $(a_L = 0, a_N \in [0,1], a_R = 1)$ and $((1) < -c, (2) = -c, (3) > -c)$
6. $(a_L = 0, a_N = 1, a_R = 1)$ and $((1) < -c, (2) > -c, (3) > -c)$
7. $(a_L \in [0,1], a_N \in [0,1], a_R \in [0,1])$ and $((1) = -c, (2) = -c, (3) = -c)$
8. $(a_L \in [0,1], a_N \in [0,1], a_R = 1)$ and $((1) = -c, (2) = -c, (3) > -c)$
9. $(a_L \in [0,1], a_N = 1, a_R = 1)$ and $((1) = -c, (2) > -c, (3) > -c)$
10. $(a_L = 1, a_N = 1, a_R = 1)$ and $((1) > -c, (2) > -c, (3) > -c)$

We can then sequentially check all ten cases,[16] which together with Assumption 1 leaves $(a_L = 0, a_N = 0, a_R = 1)$ as the unique equilibrium. □

Notice that in equilibrium, the right-turning vehicle would always ignore the stop sign. This is intuitive because (1) by Theorem 1 we must have some drivers violate the traffic rule, and (2) as right-turn vehicles have the least chances to collide, they also have the strongest incentives to disobey traffic rules.

Adapting the traffic rule One observation from Theorem A1 is that because in equilibrium all left-turning or straight-heading vehicles stop, there is never a collision even though right-turning vehicles always run the stop sign. This observation begs the question of why right-turning vehicles have to stop in the first place. Indeed, one may consider adapting the traffic rule so that all right-turning vehicles are allowed to ignore the stop sign.

Corollary A2 (A new traffic rule with four stop signs)**.** *Adapting the traffic rule so that all right-turning vehicles are not required to stop at the stop sign allows an equilibrium in which all vehicles abide by the traffic rule and no collision happens.*

Proof. Immediate from Theorem A1. □

The new traffic rule features both salient advantages and obvious flaws: On the positive side, by exempting one-third of the traffic from stopping at the crossroads, $\frac{1}{3}$ of extra gas assumption from braking at crossroads can be saved; Furthermore, given the incentive compatibility implied by the equilibrium, police forces devoted to catching stop sign violations can be reallocated toward more efficient uses. However, on the negative side, lots of four-way crossroads have only two (not four) stop signs, so a right-turning drivers approaching such

[16] There are also ways to simplify the process. For example, notice that (1) = (2) implies $a_R = a_N = 0$ (which in turn implies $a_L = 0$) and (2) = (3) implies $a_L = a_R = a_N = 0$. Furthermore, notice that when $a_L = a_N = 0$, (3) $> -c$, which implies $a_R = 1$). Therefore, we must have (1) < (2) < (3) in any equilibrium. This reasoning would immediately eliminate five scenarios.

crossroads may end up in a collision (under the new rule) if there is no stop sign against traffic from the left; Furthermore, adopting a new traffic rule may also involve costly education and initial confusion. Given these drawbacks, one may still prefer the three-sign mechanism proposed in Section 3, which does not require changing the traffic rule.

B Omitted proofs

Proof of Theorem 2. We first show that with the belief that all vehicles in the direction facing no stop signs will not stop at the crossroads, vehicles from other directions have no incentives to deviate from abiding by their stop signs. If this statement is true, then it is immediate to see that vehicles in the direction facing no stop signs indeed have no incentive to deviate from nonstop passing, believing that all vehicles from other directions will stop at the crossroad.

The payoff to a left-turning driver who faces a stop sign but does not abide is:

$$u - \frac{2 \times \left(1 - (1-\theta)\left(1 - \frac{a_L+a_R+a_N}{3}\theta\right)\left(1 - \frac{a_L+a_N}{3}\theta\right)\right) + \left(1 - \left(1 - \frac{a_L+a_R+a_N}{3}\theta\right)^2\left(1 - \frac{2}{3}\theta\right)\right)}{3} C \quad (4)$$

The intuition for (4) is that conditional on not facing a stop sign, each other direction may have no stop sign with probability $\frac{1}{3}$. Therefore, the payoff from violating the stop sign is the average of (1) over the three possible scenarios, and for each scenario, the a_L, a_R, and a_N from the direction without a stop sign are replaced by 1.

Similarly, we get the payoffs to a straight-heading/right-turning driver who faces a stop sign but does not abide to be, respectively:

$$u - \frac{\begin{array}{c}\left(1 - \left(1 - \frac{1}{3}\theta\right)\left(1 - \frac{a_L+a_R+a_N}{3}\theta\right)\left(1 - \frac{a_L+a_N}{3}\theta\right)\right) \\ + \left(1 - \left(1 - \frac{a_L}{3}\theta\right)(1-\theta)\left(1 - \frac{a_L+a_N}{3}\theta\right)\right) + \left(1 - \left(1 - \frac{a_L}{3}\theta\right)\left(1 - \frac{a_L+a_R+a_N}{3}\theta\right)\left(1 - \frac{2}{3}\theta\right)\right)\end{array}}{3} C \quad (5)$$

and

$$u - \frac{\left(1-\left(1-\frac{1}{3}\theta\right)\left(1-\frac{a_L+a_N}{3}\theta\right)\right)+\left(1-\left(1-\frac{a_L}{3}\theta\right)\left(1-\frac{a_L+a_N}{3}\theta\right)\right)+\left(1-\left(1-\frac{a_L}{3}\theta\right)\left(1-\frac{2}{3}\theta\right)\right)}{3}C \tag{6}$$

Then for a strategy profile (a_L, a_R, a_N) to constitute a Nash equilibrium, we must have the following three incentive compatibility constraints to be satisfied:

$$\begin{cases} a_L = 1, \text{ if } (4) > -c \\ a_L \in [0,1], \text{ if } (4) = -c \\ a_L = 0, \text{ if } (4) < -c \end{cases}, \quad \begin{cases} a_N = 1, \text{ if } (5) > -c \\ a_N \in [0,1], \text{ if } (5) = -c \\ a_N = 0, \text{ if } (5) < -c \end{cases}, \text{ and } \begin{cases} a_R = 1, \text{ if } (6) > -c \\ a_R \in [0,1], \text{ if } (6) = -c \\ a_R = 0, \text{ if } (6) < -c \end{cases}.$$

Notice that (4), (5), and (6) are all decreasing functions of a_L, a_N, a_R, and at $(a_L = 0, a_N = 0, a_R = 0)$, they obtain maximal values $u - \frac{8}{9}\theta C$, $u - \frac{2}{3}\theta C$, and $u - \frac{1}{3}\theta C$, respectively, which are all negative given Assumption 1. Therefore, in equilibrium, no drivers would find it profitable to run the stop sign. □

Familiar routes The proof of Theorem 2 relies on the assumption that when a driver approaches the crossroads and notices a stop sign, he is unsure of which other direction has no stop sign. While this is a reasonable assumption for drivers on unfamiliar routes, it may be less applicable for drivers on familiar routes. When drivers know ex-ante which direction at a crossroads faces no stop sign, unfortunately, the three-sign mechanism cannot establish universal traffic rule-abiding as an equilibrium anymore. However, we do not think this observation translates into a big disadvantage of the three-sign mechanism compared to the existing ones – indeed, as we have seen in Theorem A1, neither does the existing four-sign mechanism establish universal traffic rule-abiding as an equilibrium. Furthermore, one may still argue that the three-sign mechanism is superior to the existing four-sign mechanism, in that the former reduces $\frac{11}{12}$ of drivers' incentives to disobey the stop sign compared to the latter, as we see below:

Theorem A3. *With three stop signs erected at the crossroads, in equilibrium vehicles in all but one particular path have incentives to abide by the traffic rule. Specifically, if there is no stop sign for vehicles arriving from the east, then only drivers arriving from the south right-turning toward the east have incentives to run the stop sign and all others will abide.*

Proof. Without loss of generality, we assume that vehicles coming from the east do not face stop signs. Denote a_{ij} where $i, j \in \{E, W, N, S\}, i \neq j$ as the probability of running the stop sign for a vehicle arriving from direction i and heading toward direction j. Without a stop sign, drivers arriving from the east have a_{Ej} where $j \in \{W, N, S\}$. Table A2 then summarizes the payoffs from running the stop sign rule for each driver with different arriving and heading directions.

WE	$u - \left(1-(1-\frac{1}{3}\theta)(1-\frac{a_{NE}+a_{NS}}{3}\theta)(1-\frac{a_{SE}+a_{SW}+a_{SN}}{3}\theta)\right) C$
WN	$u - \left(1-(1-\theta)(1-\frac{a_{NE}+a_{NS}}{3}\theta)(1-\frac{a_{SE}+a_{SW}+a_{SN}}{3}\theta)\right) C$
WS	$u - \left(1-(1-\frac{1}{3}\theta)(1-\frac{a_{NE}+a_{NS}}{3}\theta)\right) C$
NE	$u - \left(1-(1-\frac{2}{3}\theta)(1-\frac{a_{WE}+a_{WN}+a_{WS}}{3}\theta)(1-\frac{a_{SE}+a_{SW}+a_{SN}}{3}\theta)\right) C$
NW	$u - \left(1-(1-\frac{2}{3}\theta)(1-\frac{a_{SW}}{3}\theta)\right) C$
NS	$u - \left(1-(1-\frac{2}{3}\theta)(1-\frac{a_{WE}+a_{WN}+a_{WS}}{3}\theta)(1-\frac{a_{SW}}{3}\theta)\right) C$
SE	$u - \left(1-(1-\frac{a_{WE}+a_{WN}}{3}\theta)(1-\frac{a_{NE}}{3}\theta)\right) C$
SW	$u - \left(1-(1-\theta)(1-\frac{a_{WE}+a_{WN}}{3}\theta)(1-\frac{a_{NE}+a_{NW}+a_{NS}}{3}\theta)\right) C$
SN	$u - \left(1-(1-\theta)(1-\frac{a_{WE}+a_{WN}}{3}\theta)(1-\frac{a_{NE}}{3}\theta)\right) C$

Table A2: Three-sign mechanism: Payoffs from running the stop sign on a familiar route

Apparently, given Assumption 1, every row in Table A2 is strictly less than $-c$ except for SE, therefore in equilibrium $a_{WE} = a_{WN} = a_{WS} = a_{NE} = a_{NW} = a_{NS} = a_{SW} = a_{SN} = 0$ and $a_{SE} = 1$. Plugging them back into the table, it is easy to verify that for drivers arriving from the east, $a_{EW} = a_{EN} = a_{ES} = 1$ is indeed optimal. □

Theorem A3 indicates that when the stop sign for vehicles from the east is removed (and drivers are aware of this fact), then all drivers have strict incentives to abide by the traffic rule, except for drivers from the south right-turning toward the east. Note that although SE drivers have strict incentives to run the stop sign, no collision happens even if the run indeed

happens. However, if one still wants such offenses to not take place, police monitoring may again be introduced. Compared to the case with four stop signs, however, our new mechanism only requires the police to monitor one specific direction, so that the increased focus may either save police expense (or as a dual problem increase monitoring effectiveness, that is, the probability of catching offenders).