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The Not-So-Fundamental Relationship Between Traffic Flow and Speed?

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The fundamental diagram of traffic congestion states that driving speed generally decreases with traffic flow, and that marginal decreases become more pronounced for higher flows. We find, however, that this seemingly fundamental relationship breaks down when only very few cars are on the road, and speed actually increases with traffic flow. To reveal this surprising finding, we use a unique large-scale real-world dataset with per-minute traffic observations from the German Autobahn, and control for confounders of the speed-flow relationship in a fixed-effects regression model. By linking our robust results to psychological research on social interaction effects in traffic, we then discuss potential reasons for this behaviour.

Keywords: speed-flow relationship, fundamental diagram of traffic congestion, traffic psychology.
JEL: R41.

I. Introduction

Being the only driver on the road is great – you can enjoy the freedom of driving at your desired speed, completely unimpeded by other vehicles and congestion effects. Hence, the observed driving speed of drivers who are alone on the road should reflect the individual's *ideal* driving speed, given the prevailing road conditions and posted speed limits. If there are more drivers on the road, however, congestion effects can occur and slow down all drivers. The observed driving speed would thus be lower than the individually preferred or free-flow driving speed.

This relationship between traffic flow and speed is illustrated in the fundamental diagram of traffic congestion, which is depicted in Figure 1 and shows the fundamental relationships between traffic density (cars/km), traffic flow (cars/hour), and driving speed (km/hour). In the course of our study, we focus on the speed-flow relationship, and in particular on situations in which traffic density is rather low and relatively few cars are on the road. This corresponds to the upper branch of the speed-flow diagram, i.e. the congested branch. Consequently, we disregard the lower hypercongestion branch where traffic density is so high that traffic flow and driving speed both break down.[1]

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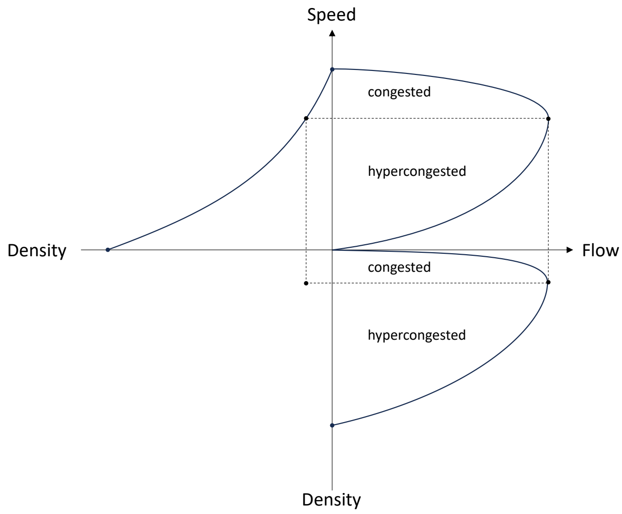
[1] In the engineering literature, the upper branch is often referred to as "uncongested" and the lower branch as "congested". In our paper, however, we follow the economic literature and refer to the upper branch as "congested" or "normally congested", and to the lower branch as "hypercongested".

Figure 1. : Fundamental diagram of traffic congestion (adapted from Small and Verhoef, 2007)



Focusing on the congested branch of the speed-flow diagram, both the theoretical and the empirical literature find that mean driving speed remains constant or decreases with traffic flow when the traffic flow is low, and it decreases unambiguously when traffic flow is higher (Daganzo, 1997; Greenshields, 1935; Small and Verhoef, 2007; Van Aerde and Rakha, 1995; Wu, 2002).

In contrast to this seemingly fundamental relationship, however, we find that the speed-flow relationship, at least on the German Autobahn, is not as clear-cut as one might think. Surprisingly, the average driving speed appears to *increase* with traffic flow when traffic flow is very low. In order for this initially positive relationship to become visible, we use a unique large-scale real-world dataset with per-minute traffic observations. This is crucial, since only per-minute data enable us to draw conclusions about the speed-flow relationship when drivers are almost alone on the road.

When plotting our data, we indeed find that the level of data aggregation plays a crucial role for the shape of the visible speed-flow relationship, which is illustrated in Figure 3 in section 2.2. Plotting our data on the usual hourly temporal resolution leads to the well-known speed-flow diagram, i.e. driving speed generally decreases with higher traffic flow (e.g. Geistefeldt, 2016). Plotting our data on the per-minute temporal resolution, however, leads to an inverted u-shaped speed-flow relationship, which is visible over data from all 59 measuring stations. It appears that the average driving speed gradually increases with traffic flow until around 10 to 15 vehicles per minute, and then declines for each additional vehicle.

One immediate concern with the indicated positive speed-flow relationship at very low traffic flows is potential confounding caused by bad driving conditions. Heavy rain, bad visibility, or slippery roads might lead to low traffic flows and low driving speeds at the same time. To address these concerns and estimate the undistorted impact of traffic flow on driving speed, we utilize a fixed effect regression model and account for driving condition variables such as weather and visibility, as well as the number of trucks. Our regression results underline a robust inverted u-shaped speed-flow relationship, which other research was not able to find due to the higher level of data aggregation. For each additional vehicle on the road, we find that average driving speed increases significantly, and peaks at eight vehicles. Average driving speeds are then 0.99 kph higher than a situation with only one car on the road. From then on, each additional vehicle decreases average driving speed. Only when traffic flow is higher than 20 vehicles per minute, does the average driving speed become lower than for one car.

But what can cause individuals to deviate from their ideal single-driver speed and drive faster when more vehicles are on the road? By discussing our results against the backdrop of the literature on traffic psychology, we provide potential reasons for this behaviour. Because driving takes place in a social environment, individual drivers influence each other through their respective actions (Haglund and Åberg, 2000). These social interactions could lead to the observed initial speed increases if drivers think that others are faster, hence wanting to increase their speed to adhere to social norms (Zaidel, 1992), avoid the social pressure of being seen as a bad driver (Elliott et al., 2005; Yannis et al., 2013), or drive in a crowd with homogenous speed (Connolly and Åberg, 1993). Moreover, individual drivers simply might like to overtake others to gain a feeling of superiority or to avoid driving directly behind other drivers (Stephens and Groeger, 2011). Although we cannot exactly identify the psychological mechanisms behind our findings, we argue that a mixture of the above arguments may reasonably contribute to the initially increasing speed.

The remainder of this paper is structured as follows. Section II describes the data and illustrates the speed-flow relationship for different temporal resolutions. In Sections III, we conduct our regression analyses and discuss the findings against the backdrop of the literature on traffic psychology. Section IV concludes.

II. Data and descriptive analysis

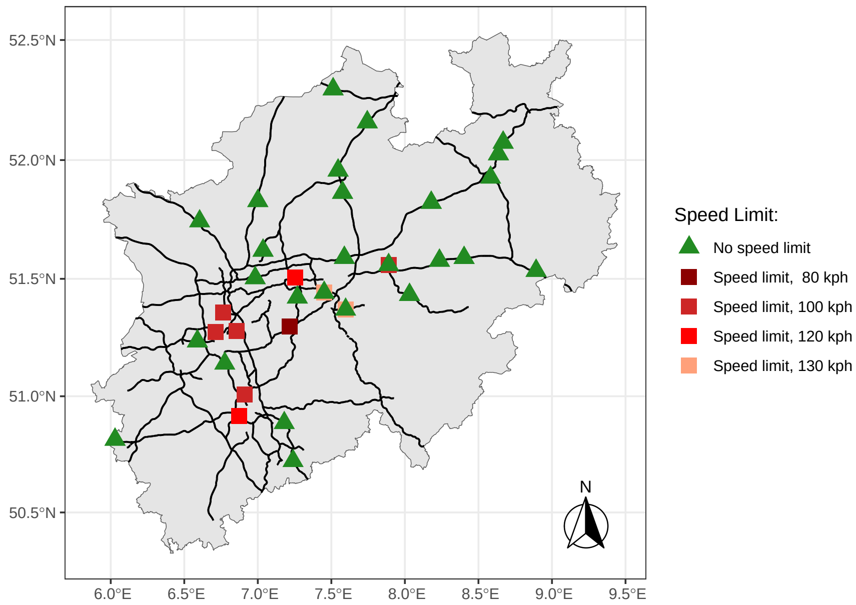
A. Data on traffic flow and speed

We analyze traffic flow and speed data from 59 measuring stations on the German Autobahn between January 2017 and December 2023.[2] All of these stations are located in North Rhine-Westphalia, the most populous state in Germany, encompassing 30 % of the national Autobahn network. Our sample consists of 44 measuring stations without a speed limit, and 15 with a speed limit (see Figure 2). This proportion roughly corresponds to the share of speed-limited and not-limited Autobahn kilometers (Bauernschuster and Traxler, 2021). Of those limited measuring stations, there is one with a posted speed limit of 80 kph, nine with 100 kph, three with 120 kph, and two with 130 kph. Traffic flow and average driving speeds are recorded by induction loops under the road surface on a per-minute basis, separately for cars and trucks, and for each driving lane. As the data has already been aggregated on a the per-minute basis by Autobahn GmbH, the speed can be regarded as time-mean speed.

To minimize the influence of road characteristics on speed, the measuring stations were selected to avoid curves or proximity to freeway ramps. Moreover, we ensure analyzing free-flow speed data by excluding observations with an average speed of below 70 kph (Brilon et al., 2005) due to traffic breakdowns, e.g. con-

[2] Provision of raw data by Autobahn GmbH des Bundes, branch office Rheinland, further processing and presentation of results by the authors.

Figure 2. : Location of measuring stations



structions sites or heavy snowfall. Our final dataset then consists of 143 million observations, and accounts for more than 2.5 billion cars and 540 million trucks.

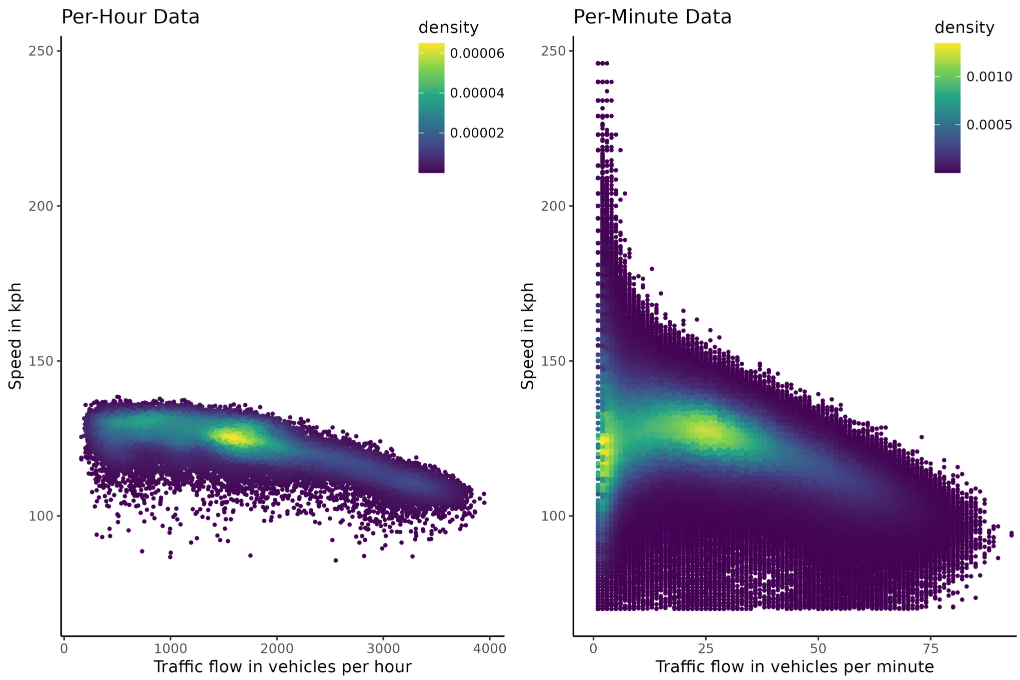
B. The speed-flow diagram for different temporal resolutions

Previous analyses on the relationship between traffic flow and driving speed are often based on hourly data. Plotting data at this temporal resolution leads to the well-known speed-flow diagram, and we depict the congested branch on the left in Figure 3 for one selected measuring station on the German Autobahn A52 (ID: 52.009_HFB_SW) with two lanes and no speed limit. Here, brighter colors indicate that a particular speed-flow combination is observed more frequently than darker-colored speed-flow combinations. In line with the literature, we observe that driving speed generally decreases with higher traffic flow, although this negative relationship is not clearly visible at lower traffic flows. Due to the exclusion fo speeds below 70 kph, only the congested branch is visible.

While this diagram allows drawing conclusions about the general relationship between driving speed and traffic flow, it is inadequate for studying driving behavior if there are very few cars simultaneously on the road. For this particular measuring station, the minimum hourly traffic flow is around 70. This hour probably includes instances when cars are alone or almost alone on the road, but the temporal resolution and aggregation at the hourly level prevents zooming in on these instances.

To learn more about driving behavior if there are few cars simultaneously on the road, we then use a large and unique dataset with driving speed and traffic flow data per minute. The right-hand-side in Figure 3 illustrates these per-minute observations for the same measuring station and the same observation period. Hence, the only difference between the left and right side of Figure 3 is the temporal resolution of the data. Using per-minute data, we have less aggregation

Figure 3. : Speed-Flow-Diagram for hourly (left) and per-minute (right) data



and a much wider variation in driving speed and traffic flow values. Now, we even have many observations where drivers are alone on the road[3], and also many where very few other drivers are present.

Surprisingly, the right-hand-side of Figure 3 indicates that the relationship between traffic flow and driving speed appears to be positive when there are only few cars on the road, which becomes especially apparent when focusing on the brighter-colored, more frequent speed-flow observations. Such a positive relationship implies that if very few drivers are on the road, the presence of an additional driver would *increase* average driving speed. Hence, this illustrated speed-flow relationship based on per-minute data, would stand in stark contrast to previous findings made with hourly data. It should be noted, however, that if traffic flow is higher than approximately 15 cars per minute, the speed-flow relationship first becomes constant and then negative, thereby conforming to conventional wisdom on the speed-flow relationship.

III. Estimating the speed-flow relationship

A. Empirical strategy

One immediate concern with the indicated positive relationship between traffic flow and driving speed at very low traffic flows is potential confounding by bad driving conditions. Heavy rain, poor visibility, or slippery roads might lead simultaneously to low traffic flows and low driving speeds.

To identify the impact of traffic flow on driving speed, we exploit substantial variation in traffic flow values between per-minute observations and use a regression model that controls for a rich set of potential confounders. In particular, we

[3] We define observations with only one car per minute as a situation in which the driver is alone on the road.

control for the impact of weather on traffic speed by including hourly data on air temperature (in °C), precipitation (dummies for no rain, light rain, rain), and wind speed (in m/s) from the German Meteorological Service (DWD). Weather data is taken from the nearest weather stations to each measuring station. Moreover, we control for daylight and twilight (Wessel, 2022).

In addition to weather and visibility, we control for fuel prices, which are published by the Market Transparency Unit for Fuels and retrieved from Tankerkönig. To account for the share of vehicles with different conventional engines, we follow Hagedorn et al. (2023) and calculate the weighted average daily fuel price of E5, E10 and Diesel.[4] Furthermore, we use data on the unemployment rate of North Rhine-Westphalia (Federal Employment Agency) and the Covid Stringency Index (Mathieu et al.) in order to control for the effects of the Covid-19 pandemic on mobility. Additional dummy variables account for school and public holidays.

When setting up our regression model, we do not impose any restrictions on the functional form between traffic flow and average driving speed by using dummy coding for the traffic flow variable. This implies that each potential traffic-flow value enters the regression model as a separate dummy variable[5]. The resulting regression model for estimating the relationship between traffic flow and average driving speed can then be formalized as follows:

$$(1) \quad \mathit{Speed}_{i,t} = \sum_{j=2}^{n} \beta_j \times Car\ Flow_{j,i,t} + \mathbf{x}'\boldsymbol{\eta} + \lambda_i + \lambda_{h(t)} + \lambda_{w(t)} + \lambda_{m(t)} + \lambda_{y(t)} + \epsilon,$$

where $\mathit{Speed}_{i,t}$ is the average driving speed per minute at measuring station i and time t. The variables $Car\ Flow_{j,i,t}$ are separate dummy variables that take on the value 1 if the observed car flow at station i and time t is equal to the running index j, and zero otherwise. The regression coefficients β_j then indicate the change in driving speed if the observed traffic flow is equal to j, compared to the reference speed when traffic flow is equal to 1. The term $\mathbf{x}'$ reflects the control variables outlined above, as well as separate dummy variables for the number of trucks on the road which are similarly coded as for cars. In addition, the various fixed effects are denoted by λ for measuring station i, hour $h(t)$, weekday $w(t)$, month $m(t)$, and year $y(t)$; ϵ denotes the error term.

B. *Regression analysis*

Results

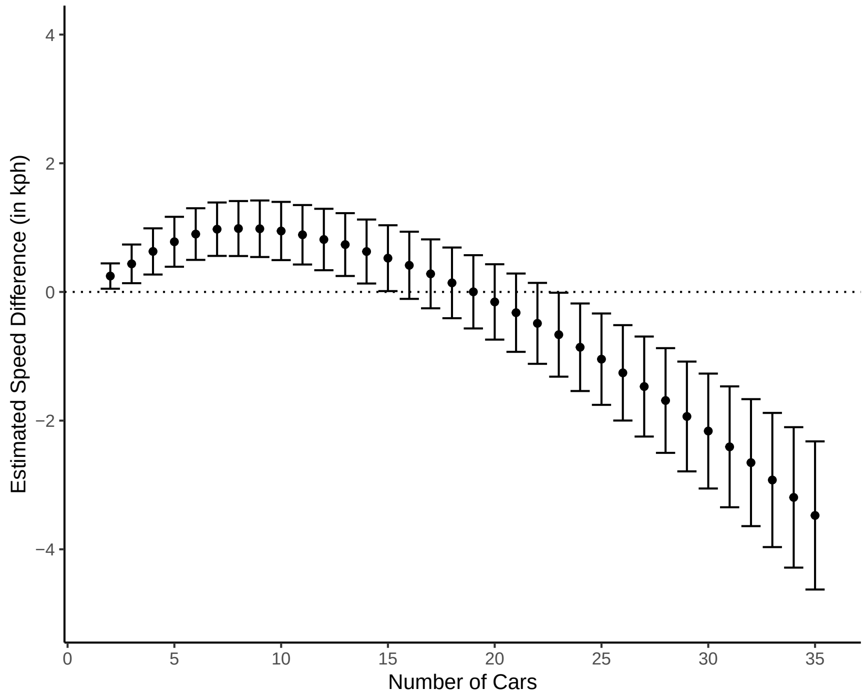
The regression coefficients and the corresponding confidence intervals are plotted in Figure 4, and the normalized reference speed of one single driver is indicated by the dotted line. Although we do not impose any restrictions on the functional relationship between traffic flow and driving speed, we find a smooth inverted u-shaped speed-flow relationship. Hence, the regression analysis basically confirms the main finding from our descriptive analysis.

If there is only one driver on the road and an additional driver enters the road, the average driving speed increases by 0.25 kph. From then on, each additional

[4] Due to the low share of battery electric cars of only 1.3 % in 2022 in Germany (KBA, 2022), we do not consider charging costs for battery electric cars.

[5] Since we are only interested in the initial speed increase, i.e. the left part of the congested branch, we only consider observations with no more than 35 cars per minute.

Figure 4. : Regression coefficients for overall data



driver further increases the average driving speed of all drivers in the same minute interval. The driving speed is highest when there are eight cars per minute on the road, and in such situations, it is 0.99 kph higher than if only one car is on the road. From then on, average driving speed begins to decrease with higher traffic flows, and only become significantly lower than for one car if there are 23 cars per minute on the road.

Why does speed initially increase with traffic flow?

Although our results of initially increasing speeds seem to be counterintuitive at first glance, we continue by providing several reasonable explanations for this surprising finding by linking our large-scale real-world traffic data with findings form experimental research in traffic psychology.

Generally, drivers are heterogenous with respect to their characteristics, such as driving skills, speed preferences and caution (Sagberg et al., 2015), and can be defined as individuals who are influenced "by the social environment consisting of other road users, general social norms, traffic-related rules of conduct, and their representations" (Zaidel, 1992, p. 585). In the following, we focus on three important social factors that might trigger drivers to drive faster than if alone on the road.

Social norms and social pressure

As one form of social interaction, drivers compare their speed to the perceived speed of others. The perception that other drivers are faster – irrespective of whether this is actually true or misperceived, as some drivers systematically underestimate their own speed and overestimate that of others (Åberg et al., 1997;

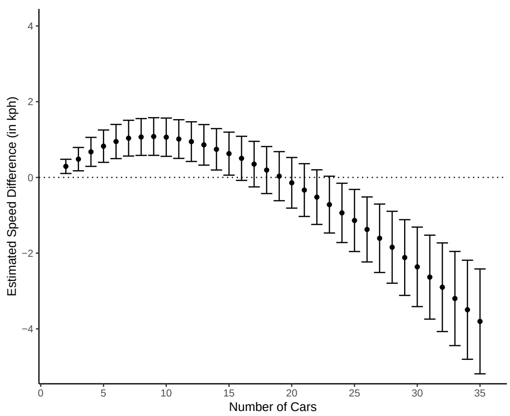
Recarte and Nunes, 1996; Schütz et al., 2015) – may be a reason to increase one's own speed and drive faster than the ideal single-driver speed.

Against this backdrop, social norms and social pressure could impact on individual driving behavior. Social norms in driving can be viewed as a collective reflection of others' opinions (Zaidel, 1992), influencing our own decision-making process based on what we think what others think of us (Messick and Brewer, 2005). Therefore, drivers may imitate others by adapting to their driving speeds (Arthur, 2011; Zaidel, 1992) in order to change how others perceive them. As a consequence, drivers influence each other's speed decisions (Haglund and Åberg, 2000).

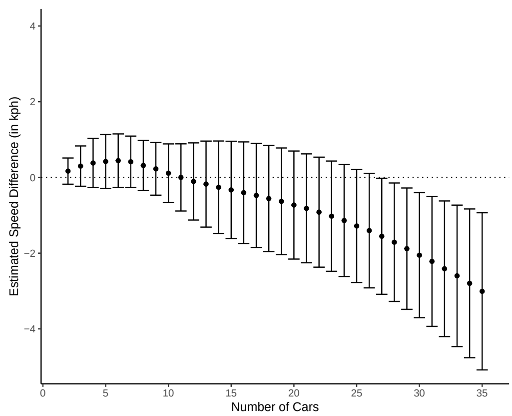
Moreover, Yannis et al. (2013) state that "slow drivers" are often associated with a lack of self-confidence, lower driving ability and insecurity. To avoid being included in this group, it seems a reasonable explanation that some people drive faster when other vehicles are around. Hence, social pressure from others and the desire to conform and be accepted by other drivers on the road may have a significant impact on one's own driving-speed decision (De Pelsmacker and Janssens, 2007; Elliott et al., 2005; Groeger and Chapman, 1997).

The impact of social pressure and social norms on driving-speed decisions might be influenced by the presence of speed limits. In Figure 5, we plot the coefficients separately for Autobahn sections without and with a speed limit. Especially on sections with no speed limit, driving fast could be perceived as a social norm and thereby enhance social pressure. Hence, we can observe that each additional car statistically significantly increases average speed at very low traffic flows (see Figure 5a). In contrast, Figure 5b suggests a similar pattern for Autobahn sections with a speed limit, although these changes are no longer statistically significant. On these sections, social pressure might be inhibited by the fact that driving fast is not considered the norm. Hence, drivers base their individual speed decisions on the speed limit and less on the speed of others. Thus, our results indicate that the absence of a speed limit may lead to increased social pressure to drive faster than would be individually ideal.

Figure 5. : No limit vs. limit



(a) No limit



(b) Limit

Driving with the flow

Another explanation for driving faster than the ideal single-driver speed could be the desire to drive in a crowd or keep up with the flow. According to Senders et al. (1967), driving should generally be viewed as a very challenging information-processing task. Driving at a homogenous speed, however, reduces speed differences and is thus less mentally challenging (Connolly and Åberg, 1993). Because of fewer interactions, the likelihood of conflicts that could lead to collisions and traffic accidents is reduced (Aarts and van Schagen, 2006). Consequently, drivers may feel more comfortable and safer through adjusting their speed.

Since speed differences on limited sections are generally lower than on not-limited sections, there are fewer drivers who may feel the need to adjust their speed on limited sections, and average driving speed is less dependent on the presence of other drivers. This might lead to a flatter curve and a loss in statistical significance for the regression coefficients of the limited sections in Figure 5.

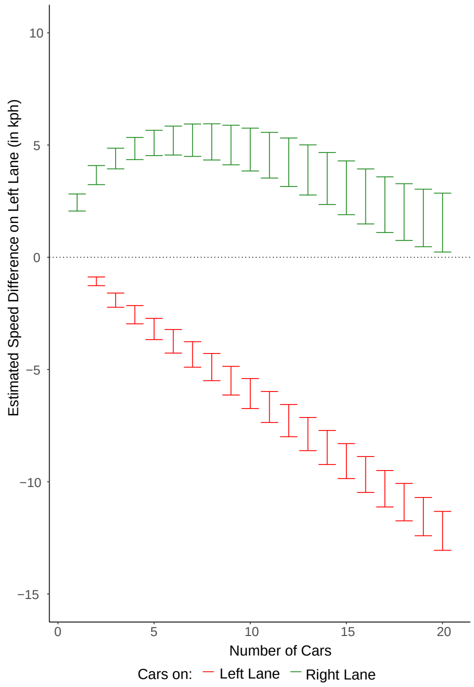
Overtaking

Another reason for the initially increasing driving speeds could be an inherent preference for driving faster than others. Some drivers might simply enjoy overtaking, which is of course only possible when other drivers are around and traffic flow permits. In addition, drivers might get a feeling of *illusory superiority* when overtaking other drivers, as this makes them feel as the faster and thus better driver. Another reason for overtaking could be to avoid anger and frustration from driving behind other vehicles (Kinnear et al., 2015; Stephens and Groeger, 2011). In line with these reasons, both Bar-Gera and Shinar (2005) and Farah and Toledo (2010) find that some drivers overtake vehicles that are equally fast or even faster than their own targeted speed, hence underlining that the presence of other drivers can lead to driving faster than the ideal single-driver speed. When looking at our data, we indeed find indications of such behavior. For this, we exploit the "Rechtsfahrgebot" on the German Autobahn, which is a law that requires drivers to adhere to the rightmost lane if traffic flow permits, thereby allowing for easier and safer overtaking in the left lanes. To analyze the determinants of driving speed in the left lane, Figure 6 then plots the estimated impact of cars in the left lane (red) and cars in the right lane (green) on driving speed in the left lane. If there are more vehicles in the right lane, there is more enjoyment to be gained and more frustration to be avoided by overtaking those vehicles, hence increasing average driving speed in the left lane.

Summary of social interaction effects

Altogether, initial speed increases can be rooted in three main explanations related to social interactions. If people think others are faster, they might increase their speed firstly due to social norms and social pressure, and secondly due to their preference for driving in a crowd with a homogenous speed. Third, some drivers might be triggered when other cars are around, and increase their speed just to overtake them and get a feeling of superiority. Although we cannot exactly identify the psychological mechanisms underlying the initially increasing speed, we argue that a mixture of the above arguments – which could be considered as complementary due to heterogeneous driving behaviour – may reasonably contribute to our findings. The social interactions between drivers may thus lead to

Figure 6. : Impact of cars in the right and the left lane on left lane driving speeds



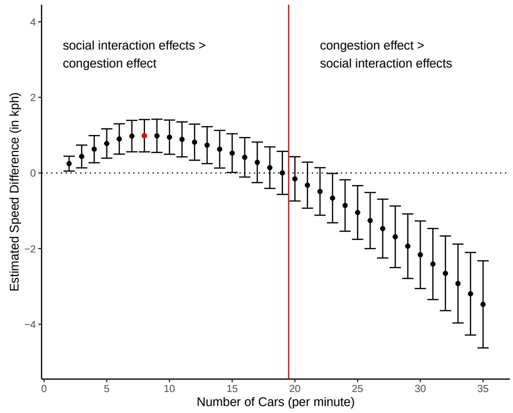
a contagion effect resulting in self-amplifying driving speeds at low traffic flow levels.

Why does speed peak, and at which traffic flow?

Based on the above explanations, one might ask why speed does not increase to the maximum that is technically possible? The decision on driving speed under specific driving conditions (e.g. road characteristics, weather, visibility) is influenced by traffic flow in two conflicting ways. On the one hand, the presence of other vehicles distorts the speed decision due to the *social interaction effects* outlined above, causing drivers to exceed their ideal single-driver speed, i.e. the speed when one is alone on the road. On the other hand, each additional vehicle on the road contributes to congestion, thereby reducing the average driving speed. In situations with very low traffic flow, the social interaction effects outweighs the *congestion effect*, initially leading to an increase in driving speeds until the maximum is reached, which is illustrated by the red point estimate in Figure 7. With only a few cars on the road, there is sufficient capacity for free speed choices. However, as traffic flow rises, congestion intensifies. The freedom of speed choice is thereby curtailed and the influence of the social interaction effects reduced. Consequently, average driving speed decreases. The vertical red line in Figure 7 depicts the point where the social interaction effects equal the congestion effect. To the right site of this point, the congestion effect outweighs the social interaction effects so that average driving speed falls below the level of only one car on the road.

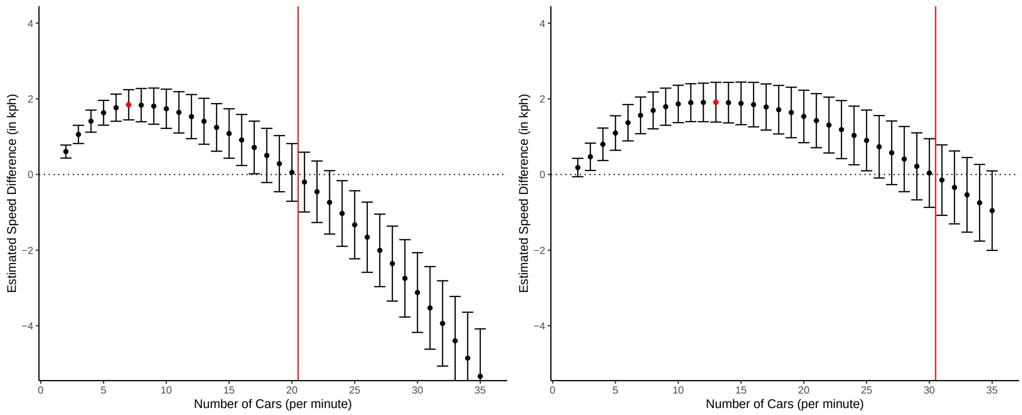
In the next step, we analyze the determination of the peak value of driving speed, i.e. the point at which the social interaction effect exceeds the congestion effect the most. We find that the location of the peak depends on the capacity of the highway section. To show this, we first conduct regressions separately for

Figure 7. : Social interaction vs. congestion effects (overall data)



Autobahn sections with two and with three lanes. As can be seen in Figure 8, the peak for three-lane Autobahn sections is at 13 cars and thus at a higher level of traffic flow than at sections with two lanes (peak at 8 cars). This pattern

Figure 8. : Two lanes vs. three lanes



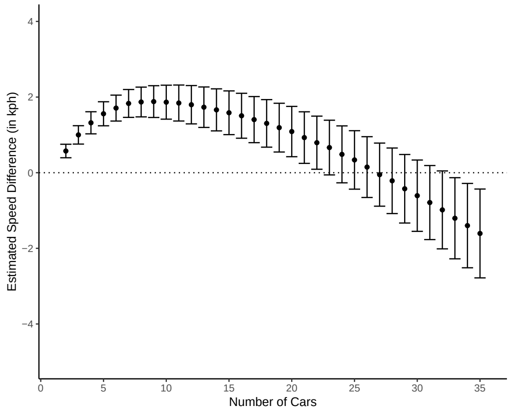
(a) Two lanes

(b) Three lanes

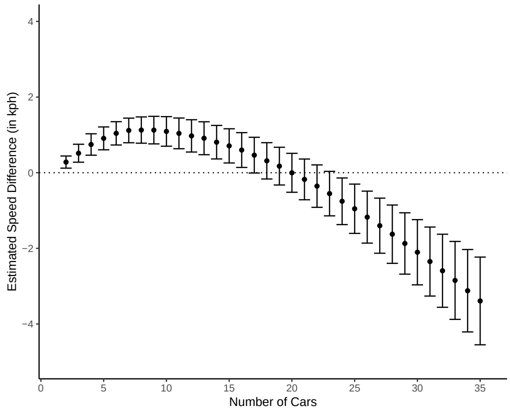
is analogous visible for the point where the social interaction effects equal the congestion effect.

Another determinant of capacity is the share of trucks. The lower the number of trucks on the road, the higher and the longer the initial increase in driving speeds (see Figure 9). Thus, the peak is shifted to higher traffic flow levels. Conversely, capacity decreases if there are many trucks on the road. This limits the freedom of speed decision and thereby the social interaction effects, such that there is no initial increase in driving speeds, but rather a lateral movement.

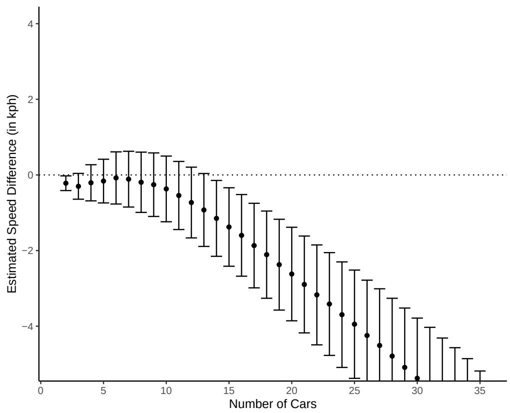
Figure 9. : Different number of trucks



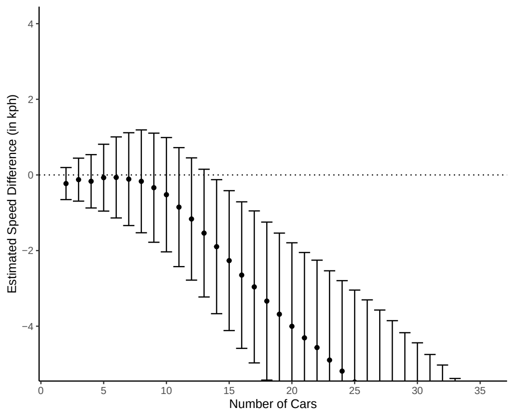
(a) 0 trucks



(b) 1 to 5 trucks



(c) 6 to 10 trucks

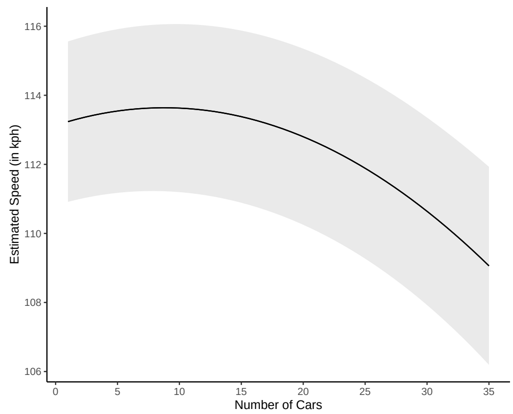


(d) More than 11 trucks

C. Robustness checks

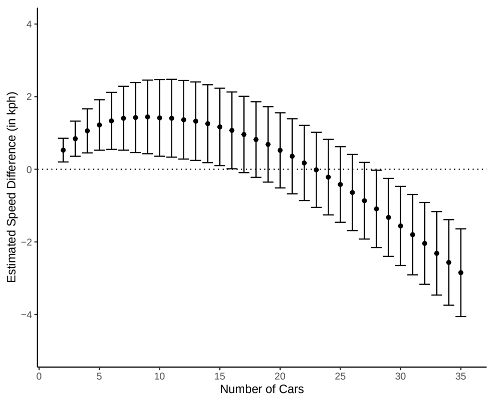
In order to verify the robustness of the inverted u-shaped speed-flow relationship, we now use a linear and a quadratic term for *Car Flow*, instead of using separate dummy variables for each car-flow value. Figure 10 plots the effect of the number of cars on speed, conditional on the mean values for all other variables. The inverted u-shaped curve confirms the robustness of our previous results.

Figure 10. : Plot for regression with quadratic relationship

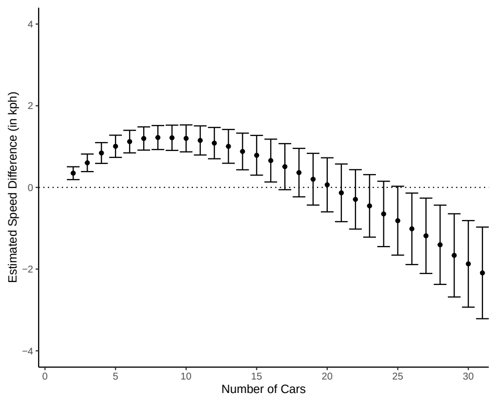


Second, we mitigate concerns that our results might be driven by the fact that bad driving conditions reduce traffic flow and driving speed at the same time. Therefore, we filter our dataset to observations with only perfect driving conditions, i.e. temperature above 4°C, no rain, no snow, no strong wind, and less than 5 trucks per minute. The results are illustrated for minutes with daylight in Figure 11a, and minutes without daylight in Figure 11b. Both Figures confirm the robustness of the inverted u-shaped relationship between speed and flow.

Figure 11. : Only perfect driving conditions



(a) With daylight



(b) Without daylight

IV. Discussion and conclusion

To summarize, we find an empirically robust inverted u-shaped speed-flow relationship. This implies that average driving speed *increases* with traffic flow when there are only very few cars on the road. This relationship only becomes visible when using per-minute traffic data, thereby ensuring that the data contains observations with very low traffic flow levels. We confirm this relationship through regression analyses that control for potential confounders, as well as through various robustness checks. Although this newly identified relationship appears to contradict previous research on the fundamental speed-flow relationship, it is consistent with findings from the traffic psychology literature. Driving speed may increase due to the complementary effects of social norms and social pressure, the preference for driving in a crowd, or simply the joy of overtaking.

We derive our findings by using a unique large-scale real-world dataset of per-minute traffic observations from the German Autobahn. Arguably, the Autobahn, with its absence of a general speed limit, is a special case and our results have already suggested that speed limits and the corresponding lower average speeds might reduce the influence of social interactions that cause drivers to increase their driving speed. Hence, it would be useful for future research to study whether our results could be upheld in different countries.

Our findings may have interesting implications for the fundamental diagram of traffic congestion, which is commonly used to illustrate the relationships between traffic flow, traffic density, and driving speed. In Figure 3, we demonstrate that our data strongly resembles the typical speed-flow relationship for the per-hour temporal resolution, thereby aligning with previous research on this issue. The novelty of our findings then relates only to the leftmost part of the upper congested branch of the speed-flow diagram, i.e. when there are very few cars on the road. For this small segment, we argue that the absence of stronger congestion effects and the predominance of social interaction effects – which have previously been ignored in this context – might lead drivers to *increase* their driving speed if other vehicles enter the road. Hence, caution should be advised when considering the speed-flow relationship for very low traffic flows, as this is a part of the fundamental diagram of traffic congestion that might not be as fundamental as previously thought.

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