Fluctuation and Noise Letters

Navigation Apps and Urban Sustainability

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The rise of socio-technical systems in which humans interact with various forms of Artificial Intelligence, including assistants and recommenders, multiplies the possibility for the emergence of large-scale social behaviour, possibly with unintended negative consequences. In this work, we discuss a particularly interesting case, i.e., navigation apps' impact on urban emissions, highlighting that the sum of many individually "optimal" choices may have unintended negative outcomes because such choices influence and interfere with each other on top of shared resources. To prove this point, we demonstrate how the introduction of a random component in the path suggestion phase may help to relieve the effect of collective and individual choices on the urban environment in terms of emissions.

1. Introduction

Emergent behaviour in complex systems can generate social problems due to collective effects: the sum of many individually "optimal" choices may have unintended negative outcomes because such choices influence and interfere with each other on top of shared resources. The rise of socio-technical systems (STS) in which humans interact with various forms of Artificial Intelligence (AI), including assistants and recommenders, multiplies the possibility for the emergence of large-scale social behaviour, possibly with unintended negative consequences [1, 11, 15, 18].

A notable example is GPS navigation systems (e.g., Google Maps, TomTom):

they suggest directions that make sense from an individual perspective but may create chaos if too many drivers are directed on the same route [8,13,19]. This was the rueful case of Leonia, a small town in New Jersey, USA. In 2017, GPS navigation apps like Google Maps, Waze and Apple Maps repeatedly rerouted drivers on congested highways through the narrow, hilly streets of Leonia, creating such congestion that, on some days, people could not get out of their driveways [8]. The police were forced to close dozens of streets to all drivers aside from residents and people employed there during the rush periods, effectively taking most of the town out of circulation for the popular traffic apps. Leonia's community is not alone: increasingly many towns globally have been grappling with the local gridlock caused by well-intentioned navigation apps.[a]

Beyond the anecdote, preliminary research shows that the impact of navigation apps on the urban environment is mixed [7,16]. On the one hand, navigation apps may provide benefits in mitigating carbon dioxide emissions [2]; on the other hand, they may increase the population exposure to pollution in densely-populated areas [14]. Overall, existing studies are sporadic and yield contradictory results, leading to a picture of the navigation apps' impact on the urban environment that is mainly unclear and incomplete.

Real-time navigation systems recommend the optimum path to reach a specific destination from a given position, taking into account the dynamically changing traffic conditions. Despite their indubitable usefulness, online navigation apps may cause various urban traffic troubles [13,19] because they are typically optimised to keep individual drivers' travel times as short as possible. Some navigation apps take into account current traffic conditions, but they do not consider the collective effects on the city that result from the aggregated drivers behaviour influenced by their recommendations, such as whether the streets can absorb the additional traffic generated by the recommender, whether that traffic compromises safety, creates more pollution, or by systematically avoiding certain areas of the cities increases segregation. The real impact of a driver's choice cannot be estimated in isolation, because it depends on concurrent choices of the other drivers in the city: if too many drivers choose the same "eco-friendly" route [9, 10], the route will become congested and thus not eco-friendly anymore. There is plenty of room for a better understanding of the impact of individual routing choices on the urban environment.

In this paper, we provide evidence that such an impact may be estimated through data-informed simulations on real-world road networks. Our study, though preliminary, clearly shows that the impact of GPS navigation apps on the urban environment is non-negligible and non-linear.

[a] `https://www.cbsnews.com/boston/news/iteam-waze-google-maps-traffic-navigation-apps-commuters`

2. Use case: a study of navigation apps' impact on emissions

Vehicular traffic represents one of the most critical hazards to urban sustainability. Cars and trucks are major pollution contributors, producing a considerable amount of pollutants such as nitrogen oxides (NO), carbon dioxide (CO_2), and carbon monoxide (CO) [3]. Pollutants are emitted directly into the air, which causes significant risks to the environment and individuals' health, especially those who live close to congested and busy roads. Consequently, monitoring air pollution plays a pivotal part in reducing its impact on the environment and humans' well-being and health risks.

Traffic congestion, a situation characterised by slower speeds, longer trip times, and increased vehicular emissions, may occur because of a miscoordination of the drivers' actions, often recommended by navigation apps. For instance, navigation apps' recommendations may lead to collective dissatisfaction when the same suggestion is given to many different drivers. If the navigator recommends that all vehicles travel on the same road to reach a specific destination, congestion may emerge.

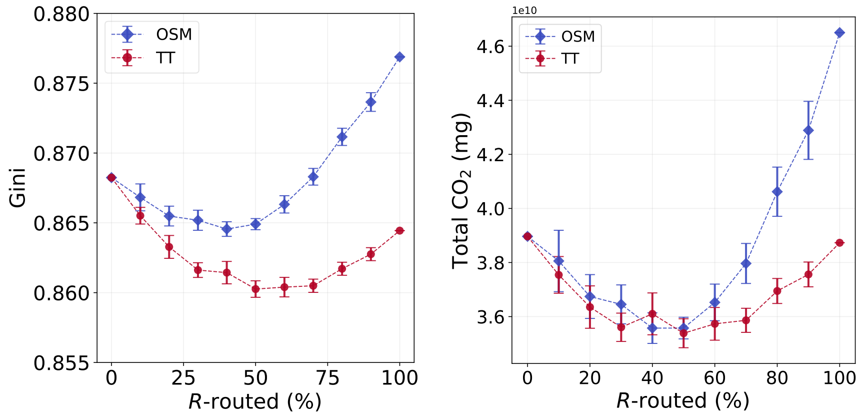
Estimating the impact of navigation systems on the urban environment is challenging: the costs and times of organising "on-road" experiments are incredibly high, and the possibility of studying and analysing different scenarios under the same initial conditions (for example, other navigation systems for the identical vehicles' origin and destination) is limited. A way to overcome these elevated costs is to use realistic traffic simulators to perform such experiments.

To provide evidence of this fact, we design a simulative framework to assess the impact of navigation systems on the urban environment in terms of CO_2 emissions and distribution on the road network [6]. We use the state-of-the-art traffic simulator SUMO [12] to design data-driven and realistic simulations of traffic under different settings to carry out "what-if" and counterfactual analysis. We consider OpenStreetMap (OSM) and TomTom (TT), an open-source and a commercial navigation system, respectively. In contrast, the vehicles that do not use a navigation system follow a random perturbation of the fastest path that mimics the imperfection and non-rationality of human drivers [17]. Indeed, individuals get distracted when driving (e.g., take wrong turns), and they lack complete knowledge of the city's traffic.

In our experiments, conducted in the city of Milan, Italy, we vary the percentage of R-routed vehicles (i.e., vehicles that follow the suggestion of a navigation app R) to the fleet circulating in Milan, estimated at 15,000 cars, to assess the impact of the rate of routed vehicles on the urban environment.

According to the results of the simulations, emissions are distributed across roads in a heterogeneous way: a few grossly polluted roads coexist with roads with significantly fewer emissions, confirming recent studies conducted using real vehicles' GPS traces [3]. Scenarios where all or no vehicles follow the navigation app's suggestions lead to the highest CO_2 emissions and the most uneven distribution of emissions per road. Furthermore, when around 50% of the cars follow the navigation app's suggestions, the impact is minimised (Figure 1). These results indicate that navigation systems seem beneficial up to a certain threshold of users after which the navigation apps have a non-negligible adverse effect on the urban environment.

Counter-intuitively, if all users blindly follow the indications of a navigation app, which provides optimised recommendations from an individual point of view, traffic discomfort emerges. On the other hand, when about half of the vehicles follow the suggestions, the diversification of the routes travelled is maximised, resulting in a better redistribution of the traffic on the road arches.



(a) Gini index

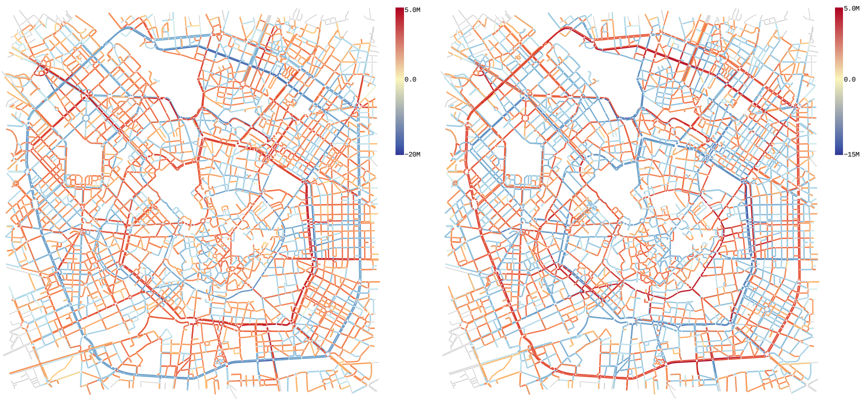
(b) Total CO_2

Fig. 1. Gini index of the CO_2 distribution (a) and total CO_2 emissions (b) varying the percentage of R-routed vehicles, for OpenStreetMap (blue) and TomTom (red). In the error bars, points indicate average Gini index (a) and total CO_2 (b) over ten simulations with different choices of R-routed vehicles chosen uniformly at random. Vertical bars indicate the standard deviation. Figure from [6].

Moreover, the fraction of routed vehicles influences the spatial distribution of emissions in the city. In particular, the comparison of 0% and 100% of routed vehicles against 50% highlights where cars are being routed, revealing emissions hot spots. Specifically, in the case of Milan, the more vehicles are routed, the fewer emissions concentrate in the city centre and the more in the external ring road; this phenomenon may arise as the navigation apps route the vehicles preferably on the city's arterial roads (such as the ring road) to keep the paths as fast as possible.

In Figure 2a, we show the difference between the per-road emissions when none of the vehicles is OSM-routed and 50% of them. Similarly, Figure 2b shows the normalised emissions difference when all cars are OSM-routed.

The injection of a random component during the path generation and suggestion phases may represent a solution to avoid suggesting only the optimal paths and the



(a) (b)

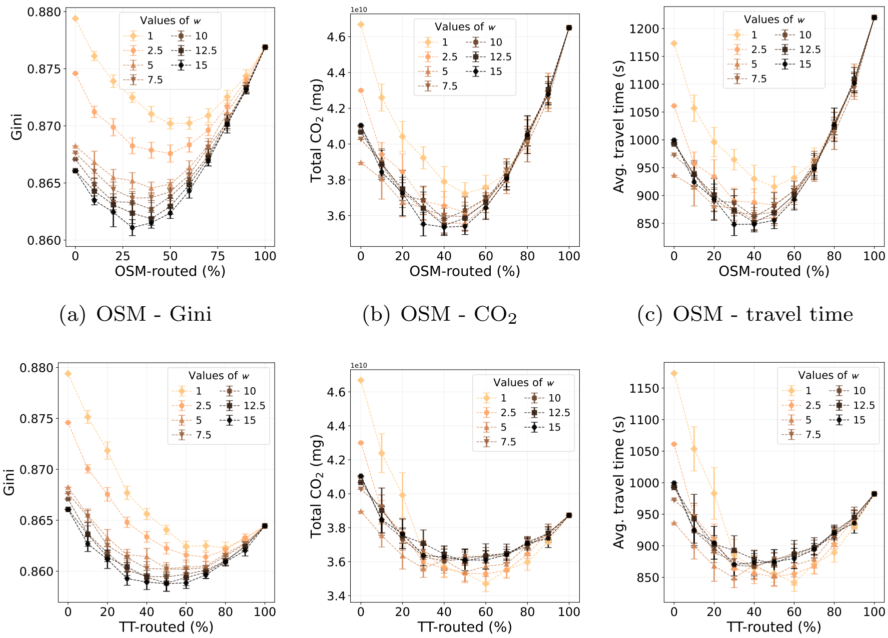
Fig. 2. The difference in the total CO_2 emitted on each road (in mg per meter of road) when: (a) none of the vehicles is OSM-routed and 50% of them are; (b) all vehicles are OSM-routed and 50% of them are. Red roads indicate a positive difference; blue ones indicate a negative difference.

risk of falling into Braess' paradox [4,5]. By introducing randomness, the navigator tends not to recommend the same route to all users who want to go from point A to point B (congesting the road) and instead proposes different routes that will no longer be optimal but will not deviate too much from the optimal one. The resulting traffic will be distributed more evenly on different paths, reducing congestion and the probability of selecting a route that other navigation systems also identify as optimal.

Preliminary results show that route perturbation is beneficial: the stronger is the random component in the vehicles' paths, the shorter their travel time and the lower the emissions in the city. The vehicles' perturbed paths are more "diverse" (i.e., they spread over more roads), thus reducing congestion and, consequently, the quantity and inequality of emissions and travel time (Figure 3).

Although our experiments use a routed/non-routed dichotomy, the situation is more complex in the real world. Multiple navigation apps coexist simultaneously (each with its heuristics and representation of urban reality), and each with a proper urban environmental "footprint". The environmental footprint of TomTom is lighter than OSM (Figure 1), suggesting that the TomTom routing algorithm recommends paths that generate a softer adverse impact on urban well-being than OSM. The situation in which multiple navigation apps coexist simultaneously suggests even more that next-generation algorithms must consider user behaviour and the collective impact of the suggestions provided and the recommendations that other navigators can provide.

This evidence suggests a need for algorithms that can exploit social and collective dimensions while simultaneously meeting individual needs. In particular, this



(a) OSM - Gini (b) OSM - CO_2 (c) OSM - travel time

(d) TT - Gini (e) TT - CO_2 (f) TT - travel time

Fig. 3. Gini index of CO_2 distribution (a,d), total CO_2 emissions (b,e), average travel time per vehicle (c,f), for different level of randomness w, varying the percentage of R-routed vehicles, for OSM (a,b,c) and TT (d,e,f).

challenge requires shifting from an individual to a collaborative and social paradigm, where the underlying shared structure, the choices of non-rational or AI-assisted agents who exploit the system and their impact on the whole society are considered.

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This section should come before the References. Funding information may also be included here.

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