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To cite this version:

Aina Rasoldier, Jacques Combaz, Alain Girault, Kevin Marquet, Sophie Quinton. How realistic are claims about the benefits of using digital technologies for GHG emissions mitigation?. LIMITS 2022 - Eighth Workshop on Computing within Limits, Jun 2022, Virtual, France. hal-03949261

HAL Id: hal-03949261
https://hal.inria.fr/hal-03949261

Submitted on 20 Jan 2023

How realistic are claims about the benefits of using digital technologies for GHG emissions mitigation?

Aina Rasoldier
Univ. Grenoble Alpes, Inria, CNRS,
Grenoble INP, LIG
Grenoble, France
aina.rasoldier@inria.fr

Jacques Combaz
Univ. Grenoble Alpes, CNRS,
Grenoble INP, VERIMAG
Grenoble, France
jacques.combaz@univ-grenoble-alpes.fr

Alain Girault
Univ. Grenoble Alpes, Inria, CNRS,
Grenoble INP, LIG
Grenoble, France
alain.girault@inria.fr

Kevin Marquet
Univ. Lyon, INSA Lyon, Inria, CITI,
EA3720
Villeurbanne, France
kevin.marquet@inria.fr

Sophie Quinton
Univ. Grenoble Alpes, Inria, CNRS,
Grenoble INP, LIG
Grenoble, France
sophie.quinton@inria.fr

ABSTRACT

While the direct environmental impacts of digital technologies are now well documented, it is often said that they could also help reduce greenhouse gas (GHG) emissions significantly in many domains such as transportation, building, manufacturing, agriculture, and energy. Assessing such claims is essential to avoid delaying alternative action or research. This also applies to related claims about how much GHG emissions existing digital technologies are already avoiding.

In this paper, we point out critical issues related to these topics in the state of the art. First, most papers do not provide enough details on the scenarios underlying their evaluations: which hypotheses they are based on and why, and why specific scenarios are chosen as the baseline. This is a key point because it may lead to overestimating the current or potential benefits of digital solutions. Second, results are rarely discussed in the context of global strategies for GHG emissions reduction. These leaves open how the proposed technologies would fit into a realistic plan for meeting current GHG reduction goals.

To overcome the underlined limitations, we propose a set of guidelines that all studies on digital solutions for mitigating GHG emissions should satisfy, point out overlooked research directions, and provide concrete examples and initial results for the specific case of carpooling.

KEYWORDS

digital solutions, environmental assessment, avoided environmental impacts, methodology guidelines, greenhouse gas emissions, regular carpooling platforms

Reference Format:
Aina Rasoldier, Jacques Combaz, Alain Girault, Kevin Marquet, and Sophie Quinton. 2022. How realistic are claims about the benefits of using digital technologies for GHG emissions mitigation?. In *LIMITS '22: Workshop on Computing within Limits, June 21–22, 2022.* https://doi.org/10.21428/bf6fb269.6d7bd21b

1 INTRODUCTION

1.1 Context and motivation

Tackling climate change[1] requires a massive reduction of global greenhouse gas (GHG) emissions. According to the IPCC, GHG emissions pathways consistent with limiting global warming to 1.5°C need a steady decline to reach net-zero levels around 2050 [1], but how to practically implement such emissions decline is less clear. There is a general agreement that if more efficient technologies could be useful, relying solely on them is not realistic [2]. Behavioral, organizational, and systemic transformations are necessary, and for that, we need urgent and strong actions from governments and institutions [3].

In this context, various scenarios at various scales have been proposed to drive down emissions so as to meet the 1.5°C target. Very high-level worldwide scenarios expressed in terms of Shared Socioeconomic Pathways (SSPs) [4, 5] are a precious help, but they are so abstract that quantifications can vary a lot [6, 7]. Smaller-scale scenarios for specific countries have also been proposed, either in non peer-reviewed reports [8–12], or in scientific studies [13–15].

The implications of the aforementioned pathways on digital technologies are, however, not consensual. On the one hand, the direct environmental impacts of these technologies are by now well documented [16]. Despite huge energy efficiency improvements, the carbon footprint of ICT is growing, mainly because of growing affluence (i.e., intensification and diversification of uses) and most certainly due to rebound effects [16, 17]. Whether digital technologies should be developed (but with energy gains) or inhibited remains, however, highly controversial.

LIMITS '22, June 21–22, 2022,

https://doi.org/10.21428/bf6fb269.6d7bd21b

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[1] Although we choose in this paper to discuss only climate change mitigation, the limitations that we identify and the guidelines we propose could (and should) be generalized to other environmental impacts.

On the other hand, many people in politics, industry, and research present digital technologies as a powerful tool to help reduce GHG emissions significantly in domains such as transportation, building, manufacturing, agriculture, and energy — mainly through optimization and substitution effects. Proper evaluation of these claims about the amount of GHG emissions currently avoided using digital technologies and, more importantly, about their potential for GHG emissions reduction in the near future is essential for two reasons. First, unfounded claims about the positive impact of digital "solutions" for GHG emissions mitigation could be used to delay regulation of the ever-expanding information and communication (ICT) sector and its direct environmental impacts. Second, these claims could also delay alternative action or research in the aforementioned domains if the potential of digital solutions proves to be overestimated.

1.2 Contribution

In this paper, we investigate state-of-the-art evaluations of the current or potential benefits of digital solutions so as to determine whether they indeed support the claim that these technologies can contribute significantly to GHG emissions mitigation strategies.

We point out several recurring issues in these evaluations. In particular, most papers do not provide enough details on the scenarios underlying their evaluations: which hypotheses they are based on and why, and why specific scenarios are chosen as the baseline. This is a key point because it may lead to overestimating the current or potential benefits of digital solutions. Another critical issue is that results are rarely discussed in the context of global strategies for GHG emissions reduction. These leaves open how the proposed technologies would fit into a realistic plan for meeting current GHG reduction goals.

Based on these observations, we propose a set of guidelines that should be followed by studies on digital solutions for mitigating GHG emissions. These guidelines aim to help rigorous design assessments and avoid issues seen in both grey literature and academic research, even if we focus mainly on studies from fields linked to ICT and computer sciences. We discuss these guidelines in the specific context of digital platforms for carpooling. Our work also underlines overlooked research directions.

This paper is not an exhaustive survey of the current state of the art. Still, we believe that the large number of examples from which we draw our conclusions should alert the research community to the need to better evaluate the current or potential benefits of digital solutions for GHG emissions reduction. Some of the issues pointed out here are well known by many, but they are often overlooked by the ICT community and, to the best of our knowledge, never addressed jointly. Our objective in this paper is thus to insist on the minimum requirements that evaluations of digital solutions for GHG emissions reduction should fulfill.

1.3 Outline

The paper is organized as follows. In Section 2, we underline frequent shortcomings in the evaluation of the current or potential benefits of using digital solutions for GHG emissions mitigation. Section 3 then proposes a set of guidelines that sketch what a rigorous methodology for performing such evaluations should look like. We discuss these guidelines in the specific context of digital platforms for carpooling in Section 4 and conclude in Section 5.

2 COMMON LIMITATIONS OF THE EVALUATIONS OF THE (POTENTIAL) BENEFITS OF DIGITAL SOLUTIONS

This section discusses common issues we have identified in papers evaluating the current or potential benefits of digital solutions for reducing GHG emissions. We consider these issues sufficiently problematic to make any claims about the benefits of the digital solutions studied in these papers doubtful. This is, by far, not an exhaustive overview, nor is it based on a systematic literature review. Still, we believe the presented shortcomings are frequent enough to deserve further discussion on how to detect and avoid them.

2.1 Limited scope

Hilty and Aebischer [18] classify the environmental impacts of ICT according to three levels (the so-called LES Model):

- **Life-cycle impacts.** These are the direct effects that correspond to the environmental "cost of providing ICT services."
- **Enabling impacts.** These are the "effects of applying ICT."
- **Structural impacts.** These are the systemic effects, "the long-term reaction of the dynamic socio-economic system to the availability of ICT services."

Life-cycle impacts are by nature negative and should be assessed with Life Cycle Assessments (LCAs) of ICT hardware and associated infrastructures (buildings, cooling, etc.). In contrast, both enabling and structural impacts can be either negative or positive. A comprehensive evaluation of the current or potential benefits of a digital solution for GHG emissions mitigation should estimate the net result of all these effects. Bieser and Hilty [19] concluded that structural impacts tend to be underexplored by the literature, based on a systematic review of existing assessments of environmental effects of ICT. In general, ignoring life-cycle or structural impacts could lead to anticipating benefits from using digital solutions that are not realistic.

Life-cycle impacts are ignored. For example, Rolnick et al. [20] propose a literature review on the application of machine learning to address climate change. Among the selected papers, 57 belong to applications domains having high potential for climate change adaptation or mitigation, according to [20]. Unfortunately, Ligozat et al. [21] show that none of the 57 papers provided an evaluation of the carbon footprint related to the technologies involved in the proposed solutions.

When properly conducted, LCAs of ICT-based solutions may display little to no environmental benefits if enabling effects are balanced out by direct effects. For illustration, Ipsen et al. [22] use a combination of LCA and Urban metabolism to assess the environmental impact of Smart-City solutions, which are at first glance beneficial for the environment. Urban metabolism is a model accounting for the flows of energy and resources of an urban system (e.g., a city). The evaluation encompasses damage to human health, damage to ecosystems and resource availability, and their causes. This publication shows that when considering cradle-to-gate impacts, the studied "smart solutions" are only marginally beneficial to the environment (and to climate change in particular), or even can be detrimental. This is mainly due to the impacts of the production stage that balance out the benefits expected in the use phase.

Life-cycle impacts are also often ignored for optimizations of ICTs themselves. For example, the literature on "green" mobile networks shows how 5G could reduce energy consumption thanks to energy efficiency improvements. Still, it does not consider the grey energy necessary for producing and deploying new base stations (e.g., Tombaz et al. [23]). Whether the claimed energy savings outweigh the embodied emissions of new infrastructures strongly depends on the electricity mix powering the network, and to the best of our knowledge, this is not addressed by such literature. In fact, in some cases, the embodied emissions can represent a substantial fraction of the carbon footprint of networks, e.g., 47% according to Lees Perasso et al. [24] for France.

Structural impacts are ignored. In addition to life-cycle impacts being ignored, efficiency benefits could also be taken back by rebound effects: by drastically improving network bandwidth, latency, capacity, and availability, 5G is expected to intensify and diversify network uses and induce traffic growth, as 3G and 4G already did.

Rebound effects are part of the structural and systemic effects of ICT. They are usually excluded from quantitative evaluations of emissions reduction in the ICT research community and, in general, insufficiently discussed. For example, Martinez and Viegas [25] evaluate the potential environmental benefits of a fleet of shared autonomous vehicles in a fictional scenario for Lisbon. By fixing travel demand as of today, this scenario does not take into account rebound effects due to, e.g., decreased costs and congestion and lower parking space requirements. The authors recognize that, if not properly regulated by public policies, the advent of autonomous vehicles could also lead to a large increase in vehicle miles traveled and congestion, as explained by Pakusch et al. [26], Wadud et al. [27], Coroamă and Pargman [28].

2.2 Implicit hypotheses

Evaluating the benefits of a digital solution for reducing GHG emissions requires comparing estimates of (a relevant subset of global) GHG emissions *with* that solution against estimates *without* that solution. This applies to already deployed solutions as well as proposed solutions for the future. Let us now discuss two recurring issues in the state of the art that are related to the hypotheses underlying the proposed solutions and the baseline against which they are compared. These issues make it difficult, sometimes even impossible, to assess the actual or potential benefits of the technologies that are being investigated.

The baseline against which the proposed solution is compared is not sufficiently discussed. To estimate potentially avoidable GHG emissions by carpooling platforms, some assessments [29–34] assume that the difference with the baseline only lies in car mobility. Similarly, to estimate already avoided emissions by carpooling platforms, the Registre de Preuve de Covoiturage [35] (RPC), which is a French database centralizing most trips organized via carpooling platforms, compares the GHG emissions of the trips registered with the GHG emissions of the same trips if they had been made by people driving alone in their car. In other words, in both cases, it is implicitly assumed that none of the people who carpool would have used public transportation, used soft mobility, or stayed home if they had not shared the ride. While such a hypothesis may be reasonable (and we will show in Section 4 that it holds in the situation where we have studied it), it should be explained and justified. The estimated GHG emissions reduction thanks to carpooling could be largely overestimated if carpooled trips mostly replaced less emitting transportation options, which seems to be the case for long-distance carpooling platforms in France according to ADEME [36].

Many other papers compare their proposed solution against a single baseline, e.g., Li et al. [29], BlaBlaCar [30], Raballand and Laharotte [31], Hasiak and Palmier [32], Zwick et al. [33], Coulombel et al. [37]. When the study deals with the potential of a proposed solution, such a baseline is very often a Business As Usual (BAU) scenario that is not properly justified. Beyond the question of whether the BAU scenario is realistic or not, having a single baseline against which the proposed solution is compared does not allow a fair estimate of the expected benefits of the proposed solution. Consider for example Fulton et al. [38], in which three scenarios are compared. How much of the potential of the third scenario is due to autonomous cars, and how much is due to major social changes and clean energy? A proper evaluation of the potential of autonomous cars in this paper would also need to investigate a scenario identical to that third scenario except for the use of autonomous cars.

The hypotheses under which the proposed solution is studied are implicit or not sufficiently discussed. It may be the case that the hypotheses required to make the proposed solution possible are stronger than the contribution itself. Note that this is not a problem per se, as research is also important for "what if" scenarios. Still, one should be careful not to imply that technical barriers are the most challenging. The social, economic, or environmental implications of hypotheses such as reducing the number of cars drastically in a city where autonomous cars are massively deployed (e.g., Martinez and Viegas [25]) should not be underestimated. For instance, it has been shown that, depending on the assumptions made, GHG emissions can be increased or decreased by carpooling [39].

Besides, it may be the case that additional hypotheses, not strictly necessary for the proposed solution but still part of the scenario under study, are, in fact, those that make the proposed solution effective. This case is problematic because the benefits may be misleadingly attributed to the proposed solution, as is possibly the case in Fulton et al. [38]. This should, however, become clear if the baseline against which the solution is compared is properly chosen.

2.3 Disconnection from existing global scenarios for climate change mitigation

As already discussed in the introduction, global GHG emissions reduction scenarios already exist worldwide and at national levels [1, 4–15]. Contrasting these global pictures, very specific and technical optimizations are designed by engineers and researchers everyday, without a clear connection between the two. In most research papers on reducing emissions thanks to ICT, the proposed assessments are disconnected from global goals and scenarios. This is all the more regrettable since the uncertainties related to technical progress are clearly identified in global scenarios; for instance, this is a key difference in the five narratives of the Shared Socioeconomic Pathways [5]. This also has the following implications.

The expected benefits could be negligible compared to the needs. As an illustration, consider the fuel-optimized navigation system proposed by Ericsson et al. [40] for reducing car traffic emissions. The authors show it could potentially reduce by 4% fuel consumption of cars, and a further reduction of 0.04% can be achieved if real-time traffic data is used. This study for the case of Lund claims that greater benefits from using real-time data are expected in more congested areas. Compared to the magnitude of necessary emissions reductions, and considering that it relies on technologies that are not yet massively deployed, 4% seems modest if not marginal. It corresponds only to a few months in IPCC pathways (assuming they are uniformly applied to all sectors) and is, of course, largely insufficient to decarbonize passenger mobility. Reaching net-zero emissions in mobility by 2050 requires deep and large-scale transformations (such as electrification), increase in active mobility and public transit, taming urban sprawl, etc. Such transformations will drastically reshape mobility; thus, it is not clear how to extrapolate to global mitigation scenarios any benefit computed with respect to present conditions. In other words, the baseline against which proposed solutions should be compared must be based on (or at least compatible with) a global scenario. Furthermore, if its expected benefits are not sufficient to address the GHG emissions reduction challenge without being combined with other (possibly nontechnical) solutions, then the interaction between the possible solutions should be addressed.

Different solutions may not be compatible or may interact negatively. Continuing the mobility topic, to reduce GHG emissions, one may consider two policies: improving public transit infrastructures and developing dynamic carpooling services. As shown by Coulombel et al. [37], applying both policies at the same locations could be counterproductive because developing carpooling may decrease the attractiveness of public transit due to rebound effects. Depending on the application domain, estimating the magnitude and the nature (positive or negative) of the interactions between a solution and others could be as valuable (if not more) as assessing its benefits when taken in isolation.

More generally, we think that addressing systemic effects is of great importance for climate change mitigation strategies and that they are insufficiently discussed by the literature.

2.4 Unchecked uncertainties

When evaluating the (potential) benefits of a digital solution for reducing GHG emissions, as in any other evaluation context, large uncertainties can significantly impact the conclusions that one can draw from such evaluations. Most of the evaluations of environmental impacts linked to digitization do not take uncertainties adequately into account. Such uncertainties can take many forms and are often classified as aleatoric (resulting from some intrinsic randomness of the represented phenomenon) or epistemic (due to lack of data or knowledge). In our context, and consistently with Horner et al. [41] (which focuses on indirect effects), we have identified the following main issues with the state of the art.

The quality of the input data and how the corresponding uncertainty propagates are not properly addressed. To illustrate this, let us mention three influencial papers for estimating the global emissions footprint of ICT [42–44] (which are now subsumed by Freitag et al. [16]). Out of these three papers, only Belkhir and Elmeligi [44] provided intervals for the computed estimates. Generally speaking, authors strive to provide accurate estimates in a best-effort manner but fail to track how uncertainties propagate through their computations. As a result, the precision of the computed values is difficult to assess.

Note that uncertainties about input data may be very high. As an illustration, the French ADEME maintains a database called “Bilans GES”, which allows companies, organizations, and individuals to assess their GHG footprint [45]. The accessibility and the vastness of the database make it all-purpose, including evaluations of digital solutions. Data from “Bilans GES” is even a reference in some studies. For many generic products and services, it provides a mean quantity of GHG emissions, but with, often, an uncertainty of at least 40%.

Uncertainties resulting from a limited scope or implicit hypotheses are ignored. This point relates to comments made in Sections 2.1 and 2.2.

3 GUIDELINES FOR THE EVALUATION OF DIGITAL SOLUTIONS

We now compile a set of guidelines intended to avoid the limitations listed in the previous section. To further elaborate on this topic, interested readers may consider existing research [19, 41, 46–49] and grey literature [50–58] where similar guidelines are discussed.

Given the nature of these guidelines, which often aim at making explicit assumptions and choices that tend to be overlooked, making sure that evaluations are reproducible is key to make results verifiable and reusable. It is thus all the more important to make data available to the research community, to keep the infrastructure required for the evaluation the lightest possible, and to make code publicly available in open-source.

3.1 Reliance on Life-Cycle Analysis

Formalized by ISO standards 14040 and 14044, Life Cycle Assessment (LCA) is the preferred method for quantifying environmental impacts of products and services [54]. LCA is a multi-criteria and multi-stage method and thus is not limited to GHG emissions assessment. Relying on LCA for environmental assessment is essential to track potential impact shifts between stages (e.g., from use to production) and between environmental indicators (e.g., from GHG emissions to eco-toxicity).

First, any assessment should define its own goal. This guideline exists in both LCA standards and the scientific literature regarding prospective: *What is the goal of the study?* Scenarizing (see Section 3.3) only makes sense with regard to this goal [59].

Then, emissions reduction estimates for digital solutions should be based, as much as possible, on LCAs, or at least should follow the main principles of LCA (e.g., encompassing the production, use, transport, and end-of-life stages). They should include ICT equipment (terminal, servers, networks, data-centers) and associated infrastructures (buildings, cooling, etc.) [18, 52]. By definition, GHG emissions reduction is assessed through comparative LCA, for which extra care should be taken, in particular about the scope, the quality of data, and the uncertainties. A collection of specific recommendations has already been proposed in the literature [52, 54, 56].

Even if LCA is well established, it is not free of pitfalls. First, it is based on data, which raises the problem of their quality and their availability, especially in the case of ICT, which is subject to very fast technological evolutions. Second, it relies on scenarios that provide details about usage, lifetime, disposal, etc. These scenarios have potentially huge impacts on the final results and thus on the conclusions that are built upon LCAs.

These problems are exacerbated in the case of new technologies still in development, unlike already set up and operational ones. Indeed, in such a case, LCA must address unknowns about the evolution of society and about the technological environment [60]. Therefore, it is essential to build multiple scenarios when assessing the potential benefits of a solution [61], and to conduct sensitivity analyses and uncertainty evaluations. Various methodologies at the interface between LCA and scenarization are currently under study [62].

3.2 Discussion of structural effects

LCA is not intended to encompass the structural impacts of the LES Model of Hilty and Aebischer [18], nor the second-order effects as defined by Börjesson Rivera et al. [63]. ITU [53] suggests using CGE models (Computable General Equilibrium) for assessing second-order effects, but there exists no definite and complete methodology recognized by the research community. Taking into account all these effects extensively is extremely difficult (if not impossible).

Still, there exists by now a body of literature on the subject that makes it easier to provide at least a qualitative assessment of such effects. For example, Börjesson Rivera et al. [63] lists eleven second-order effects of ICT, including different kinds of rebound, induction, rematerialization, changed practice, learning, and scale effects. When second-order effects are expected to negatively affect the benefits of a digital solution, an LCA can be used to provide an upper bound on its net benefits. Besides, for application domains having known strong second-order effects, the validity and usefulness of performing an analysis that does not take them into account must be discussed since this can potentially significantly change the outcome of the evaluation.

3.3 Scenarization

Quantitatively, the assessment of the GHG emissions potentially avoidable relies on at least two scenarios: we need to know what would happen without the digital solution (*business as usual* scenarios, aka *BAU*) and what would happen with the solution (*desired* or *alternative* scenarios).

This work of scenarization should obey some guidelines that we review in the following, using the following vocabulary:

- A scenario is a *model* of reality relying on a set of *explanatory variables*, which can be of different types (from simple types such as integer to complex ones such as the one required to model a complete travel demand for a city).
- The values of some explanatory variables are changed from one scenario to another, e.g., switching from a given travel demand to a different one. They are denoted *transformative parameters*.
- Each scenario is elaborated according to one or more underlying *hypotheses*. For instance, in a transportation scenario, the travel demand can be assumed to be fixed and set to its current level [25, 40].

3.3.1 *Define relevant variables.*

Each scenario should be justified with respect to the objective of the study. This implies that the explanatory variables of each scenario should be clearly identified, and their relevance should be established with respect to the objective of the study. For instance, in the transportation domain, for decades, researchers have investigated the relevance of time and money in the choice of people for the transportation means. But, depending on the context, other variables such as the social environment of people also play an important role [64, 65].

3.3.2 *Describe the generation of scenarios.*

The comparison between scenarios should be explicit:

- Any modification of the value of an explanatory variable from one scenario to another should be identified and motivated.
- The relation between this modification and the object of study should be investigated, and it should be clear whether or not this change occurs because of, and only because of, this object of study. For instance, some GHG emission benefits may be expected by using a fleet of autonomous vehicles in a city. However, the benefits may, in fact, not be related to the autonomous nature of vehicles but rather to the mere existence of the fleet.

3.3.3 *Justify the set of scenarios.*

Even if the goal is clearly defined, if each scenario is justified, and if the comparison between them is sound, a study can introduce some bias by selecting specific scenarios among all possible ones. For example, Fulton et al. [38] should have motivated the choice of scenarios 2R and 3R and should have explained why they did not consider, among others, variants of 2R and 3R without autonomous vehicles.

Ex-ante evaluations raise specific challenges [66], particularly in the case of sustainability [67] and, even more, in presence of fast changing technologies such as ICTs [68]. Fauré et al. [62] claimed that "scenarios can be particularly relevant, yet challenging, for sectors that develop fast".

The goal of this paper is not so much to address this problem but rather to raise questions and to point to existing useful literature, and it is plethoric. The existing literature has already identified a well-known number of pitfalls to be aware of when scenarizing the future [59, 69–71]. In order to improve studies on the potential of digital solutions, it is worth referring to this literature. For instance, backcasting [72, 73] and forecasting [74] are not applicable in the same cases. A particular study may fall into different categories that are useful to identify in order to ease comparison with other studies [66].

As said at the beginning of the section, forecasting requires a specific BAU scenario. It should be carefully defined, and the concept of BAU raises questions. To which degree is the BAU scenario a realistic prediction of the future if everything is kept "as usual"? Actually, the BAU scenario embeds hypotheses corresponding to what is understood as the default actions and trends (e.g., steady exponential growth, constant levels, ...), and they should be made explicit and discussed too.

In addition to the scenarization work, the task of assessing the sustainability aspects of a future scenario is nontrivial, and for this task, various types of methodologies exist [62]. Defining the very notion of sustainability is, in itself, a challenge, and existing work often limits its scope to a specific technology perimeter and well-identified sector. Examples of such work that also follow the guidelines mentioned in this section can be found in Bonilla et al. [75] (industry 4.0) and in Zawieska and Pieriegud [76] (smart mobility). They address the sustainability of scenarios respectively for the industry 4.0 and smart mobility.

Ex-ante vs ex-post evaluations. The evaluation of the avoided GHG emissions brought by digital solutions requires conducting an *ex-post* evaluation, which also implies the construction of at least two scenarios: we need to know what happened with the digital solution (*past* or *truth* scenario), which is a model of reality in the past, and what would have happened without the digital solution (*counterfactual* scenario), based on a counterfactual explanation.

This explanation describes a causal situation in the form: "If X had not occurred, Y would not have occurred". Counterfactual reasoning requires imagining a hypothetical reality — the *counterfactual scenario* — that contradicts the observed facts. It has various benefits for sustainability evaluation [77] (mainly understanding some mechanisms and easing analysis because data are available). However, as pointed out by Heijungs and Guinée [78] in the domain of LCA, it is totally speculative and thus should be made explicit and transparent.

The link between the results of ex-post evaluations and ex-ante evaluations is not straightforward, so they should not be directly related or at least discussed.

3.4 Link to global sustainability objectives

As already mentioned, human societies must decrease drastically and rapidly their GHG emissions. Global pathways [1] and scenarios [4–15] to reach net-zero emissions by 2050 have already been proposed and discussed. Scientific work related to sustainability should, therefore, discuss the link between their object of study and those objectives and scenarios. Hence:

- If the object of study is a technological improvement (e.g., dynamic carpooling in urban areas), then the benefits allowed by this improvement should be compared with the global objectives and desirable trajectories in the application domain.
- Besides, the interactions (compatibility, counter-productive effects, etc.) between the proposal and alternative solutions should be discussed. To which extent can the proposal be effectively combined with other solutions, contributing to a rapid move towards sustainability, or, on the contrary, can it prevent the use of other solutions? Does the proposal reduce the benefits of other solutions? Showing that a scenario is the best option among several possible ones should be preferred than showing that it is just better than the BAU alone.

3.5 Discussion of obstacles and lockins

Usually, various hypotheses need to be made in scenarization processes. For instance, a scenario in which private car, bus, and taxi mobility is completely replaced by shared mobility based on an urban fleet of autonomous minivans and minibuses [25] relies on strong assumptions: autonomy must become a reality, all existing vehicles must be discarded, and people must accept giving up on private cars in favor of vehicle sharing. Of course, there are many obstacles to such hypotheses, which should be investigated. To do so, we suggest the following.

- Transformative parameters should be carefully evaluated. For instance, studies concerning mobility do not consider that anyone can walk for an hour before taking a bus.
- One should not focus on technical limits only. It is often difficult to anticipate and address non-technical limits (e.g., cultural, sociological, ...), but they can be much stronger than the technical ones. The last decade has seen the rise of methods [79, 80] to identify them, considering socio-technical transitions [81] rather than purely technical systems. These methods have been successfully applied to transportation sub-systems [82].

Moreover, studying environmental impacts often implies a lot of uncertainties, which are important to consider in decision-making: one cannot afford to bet on hazardous solutions that require decades to evaluate. This is all the more problematic since the transformations of sectors generally take time, in the same way as incentives are slow to take effect.

The above suggestions are of primary importance in the transportation domain [83] addressed in Section 4. In addition, recent studies are also of great help for identifying obstacles [84, 85].

4 APPLICATION TO CARPOOLING PLATFORMS

Let us now discuss how to apply our proposed guidelines in the context of regular carpooling platforms. The work presented here is still in progress and does not provide an exhaustive evaluation but rather a general framework for future work and initial results.

4.1 Context and motivation

Carpooling or ridesharing is a practice where multiple travelers share the same car for traveling. It can be spontaneous and informal (hitch-hiking), or done via a carpooling platform (usually smartphone applications). In terms of geographical span, it can be either short (in which case it mainly concerns regular commutes) or long distance (in which case it mainly involves ad hoc journeys, such as holiday journeys).

We focus here on regular carpooling platforms for the following reasons:

- mobility (and in particular commuting) is one of the most polluting activities, so transformational changes are necessary to achieve global GHG emissions reduction goals [86];
- carpooling with a digital platform relies on ICT, so it is consistent with our aim to study the impacts of ICT;
- carpooling is important for low carbon strategies because it is subject to promises, thus potential assessments.

Concerning the last item, a typical judgment is that carpooling reduces GHG emissions by reducing the total distance traveled by cars, by reducing the number of cars on the roads[2].

Numerous papers provide assessments of the potential of carpooling, which we refer to as *existing potential assessment* [29–34, 39]. We noticed that they either ignore second-order effects, do not provide a fair comparison with alternative solutions, or do not study the consistency with other solutions such as developing public transportation or reducing the demand (e.g., by supporting teleworking, reducing the attractiveness of cars, increasing the attractiveness of soft mobility modes, reducing the distance between home and workplace via urbanization change). Indeed, for illustration, developing carpooling can cause a rebound effect on GHG emissions due to modal shifts, as evidenced when modeling mobility thanks to a land-use/transport interaction model [37]. More importantly, existing GHG evaluations of carpooling never relate their results to global sustainability goals (see Section 2.3). These assessments require further investigation, knowing, on top of that, that their results are not always consistent.

A systematic review is needed to list all the limitations in the evaluations of the carpooling potential according to the list presented in Section 2, and to propose an assessment addressing them. Here, we address only some limitations, as this study is still in progress.

Following our guidelines (Section 3), we start our assessment by setting up our scenarization and discussing the hypotheses for the generation of scenarios, answering the limits we found in existing assessments. This assessment would include the avoided emissions in the mobility sector and the GHG emissions added by the digital infrastructure. We then discuss the structural effects of regular carpooling and their platforms, compare our avoided GHG emissions estimates to global reduction goals, and discuss the obstacles and lockins of carpooling.

4.2 Scenarization

To assess the GHG emissions in the mobility sector that are currently avoided or could be avoided in the future thanks to regular carpooling platforms, we build and compare two types of scenarios:

- **Scenarios *with platform-enabled carpooling***;
- **Reference scenarios *without these platforms***.

Avoided emissions are the difference between the emissions in these two types of scenarios. In the following, we consider only the emissions due to digital carpooling platforms and those related to mobility, assuming there is no effect on other types of emissions.

4.2.1 Digital infrastructure of carpooling platforms. Scenarios with platform-enabled carpooling require computing the emissions of the corresponding digital infrastructure. As indicated by our guidelines, the assessment of the digital infrastructure should follow LCA principles. However, reliable databases for digital services are currently missing (or are under construction), and in any case, no public data is available. Using real-world measures would require tight collaboration with carpooling platform providers, so we decided this is beyond the scope of this work in progress. We expect that the usage and the type of carpooling platform (e.g., on-demand, dynamic, static, planned, regular, or ad-hoc) will impact the infrastructure of carpooling platforms and, therefore, their emissions. We also suspect that the emissions due to the digital infrastructure of the carpooling platforms will be negligible compared to the emissions of the mobility part, but this has to be confirmed by future work. However, taking them into account will only reduce the estimated avoided emissions.

4.2.2 Mobility scenarios. Similar to existing representations of mobility (e.g., 4-step models, a widely used class of models in transport planning), we model mobility using three key concepts:

- **mobility demand:** e.g., point of origin, point of destination, day and time of departure (or arrival);
- **transport supply:** e.g., existing roads with their traffic capacity and options offered by public transportation;
- **choice model:** an assignment of a transportation mode to each journey.

Given such information, existing methodologies can compute the corresponding GHG emissions using known emission factors associated with different modes of transportation and possibly more precise characteristics [87, 88].

Demand, supply, and choice are not independent. Typically, improving road capacity or building highways would likely lead to induced demand, namely a rise in mobility demand [89, 90]. This makes it difficult to ensure comparability between reference scenarios and scenarios with platform-enabled carpooling, as we discuss in the following sections. We do not address in this paper the generation of such scenarios and leave it for future work. Instead, we focus here on key aspects of this process.

Scenarios for currently avoided emissions. For currently avoided emissions, the scenario with platform-enabled carpooling corresponds to the current situation. The reference scenario — what the current situation would be without existing carpooling platforms — is the most difficult one to build, as it needs a counterfactual analysis. In particular, one question here is what carpoolers would have done if they had not carpooled: Would they have driven alone? Would they have used public transportation? Would they have stayed home? Etc. This is the topic of Section 4.5.

Scenarios for future avoided emissions. Future mobility may differ from current mobility. Among the assessments cited in Section 4.1, Tikoudis et al. [39] is the only one which builds its scenarios based on an extrapolation of the current situation by prolongating current trends such as demography-related variables. All the other assessments cited in Section 4.1 ignore dynamics that may influence the evolution of mobility. Relevant scenarios for estimating future avoided emissions could also, rather than trying to predict future mobility, rely on global exploratory scenarios that we want to investigate (see Section 4.3).

Regarding scenarios with platform-enabled carpooling, transport supply is directly affected by carpooling platforms as these increase the possibilities to travel by carpooling. In addition, their development is often supported by transportation policies (e.g., incentives, advertisement) that may influence the mode choice. To reflect this, existing assessments either

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[2] It implies reducing GHG emissions per traveler, or increasing occupation rate of vehicles, which are usual metrics.

- use a travel matching algorithm on car journeys or all journeys,
- or apply an arbitrary and artificial increase in the share of carpooling or in the occupancy rate.

Note that the development of carpooling platforms may affect not only supply and choice but also indirectly mobility demand. Dealing with such rebound effects is the object of Section 4.4.

4.3 Obstacles and lockins

Carpooling is not only an optimization problem. Its study should encompass political and social stakes, which need a holistic point of view. Transport planners and the mentioned strategies have highlighted social acceptance as one of the most important obstacles to overstep, thanks to, for instance, incentives [91, 92].

ADEME [93], Watts [94] have listed obstacles we summarize in five types, which can influence the social acceptance of carpooling.

- **Attitude:** Fear of traveling with unknown people is a common obstacle to carpooling, especially for those to whom "the anonymity of using transit is far more appealing than the induced social climate of carpooling" [94]. Blablacar tries to overcome this obstacle with social network features in its platform: profiles, discussions, and evaluations of users are there to reassure newcomers [93].
- **Socio-cultural obstacles:** Travelers can avoid carpooling for freedom, safety reasons, or not being ready to share their vehicle. This behavior is essentially coming from an apprehension of this practice. However, this obstacle tends to reduce.
- **Urban forms:** From a structural perspective, the topology of the roads, namely the geometric shape of the road network, can be an obstacle. Manik and Molkenthin [95] concludes that carsharing would be less efficient for topologies typical of the urban area than for topologies typical of the rural area. Still, the rural area would suffer from a lack of carpoolers. Watts [94] evokes the issue of "density of work" and "density of home": dispersed homes and workplaces can limit the number of carpooling matches.
- **Travel behaviors:** As daily mobility is more complex than only commuting trips, finding matches for carpooling can be difficult. This difficulty in finding a match can be linked to the fear of not finding a trip back in the evening after work [93].
- **Cost-savings:** Cost can be a lever as well as an obstacle to increasing carpooling. Indeed, travelers would shift from car to carpooling only with an increase in fuel costs [94].

In addition, carpooling can also face a network effect, where a minimum number of carpoolers is needed to make a carpooling service practical enough to replace car habits, which is in line with social acceptance [96]. The network effect can even be necessary to set up an on-demand transport service in replacement for all other motorized modes.

Exploratory scenarios for estimating future avoided emissions could be used to investigate the impact of lifting one or several of these obstacles. This would be useful when combined with an understanding of how difficult it is to lift these obstacles.

4.4 Structural effects

According to Coulombel et al. [37], Delaunay [97], the main structural effects on mobility due to carpooling are the following:

Congestion effect: increasing the number of passengers per car decreases traffic and hence road congestion;

Route choice effect: less congested roads allow drivers to choose shorter routes;

Distance effect: trips by car are more efficient because of time costs (because of the two previous effects) and because carpooled trips are cheaper (economic costs are shared in this case); this makes longer trips possible and tolerable;

Modal shift effects: the aforementioned increased efficiency of car trips increases car attractiveness compared to alternative transportation modes;

Relocation effect (urban sprawl): the previous effect allows inhabitants to live further from the city centers and from their work, which increases travel distances;

Congestion and route choice effects are expected to act positively on emissions avoided by carpooling[3], while distance and relocation effects act negatively. For modal shift effects, this is less clear: it depends on vehicles occupancies and the emissions of the alternative modes. They are taken into account in Section 4.5. Note that structural effects on emissions of other sectors than mobility (e.g., indirect rebound effects) are beyond the scope of this paper but would be a relevant topic too.

According to Coulombel et al. [37] who simulated road traffic for Paris, thanks to a Land-Use and Transport Integrated Model for the Paris area, the net result of all these effects is clearly negative in their case. This remains true even when excluding modal shift effects. Such results are in line with older work showing that vehicle-kilometers traveled tend to increase proportionately to traffic efficiency, which is embodied in the "fundamental law of Road congestion" of Duranton and Turner [89].

Social influence is another structural effect, this one having a positive impact on carpooling spreading: "personal social networks [can] constitute an important source of explanation of activity-travel behavior", such that one's carpooling habits can influence others' traveling habits, increasing the effect of carpooling platforms [98]. However, there is no quantification of this effect in the literature.

This list may not be thorough, as it is not the first intention of the current paper. Further works are needed to make a broad panorama of the carpooling structural effects and possibly quantify them. For the moment, we rely on the negative qualitative assessment provided by Coulombel et al. [37].

4.5 Modal shift effects from carpooling

One may expect from carpooling platforms that they induce a modal shift from driving alone to carpooling. The Registre de Preuve de Covoiturage [35] (RPC) even assumes that all carpoolers would have driven alone if they had not shared the ride in its avoided emissions estimation. In reality, regular carpooling platform users may also shift from other alternative transportation modes (e.g., public transit, bicycling, or even informal carpooling). For example,

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[3] We excluded the other beneficial effects proposed by BlaBlaCar [30] because they are not backed by peer-review studies and they suffer from potential conflicts of interest.

Mericskay [99] shows that long-distance carpooling platforms induce modal shifts from train to carpooling. Increasing carpooling in daily commutes could also reduce public transit use, as shown by Coulombel et al. [37]. Evaluating modal shift effects is crucial for assessing GHG emissions reductions since these depend on the emissions associated with alternative transportation modes, which vary a lot.

Before discussing modal shift effects from the potential increase in the use of regular carpooling platforms, we propose an evaluation of these effects from existing platform usage. Our work is based on counterfactual reasoning on past data about registered carpooling done thanks to an application from Registre de Preuve de Covoiturage [35]. Technical details on the software, source code, and data used are in Appendix A.

For each carpooled trip of the RPC, we want to estimate an alternative reality corresponding to a situation in which carpooling platforms do not exist. Our preliminary results assume that *(i)* travelers would have made the same trip with an alternative transportation mode, and *(ii)* alternative transportation modes can be walking, bicycling, public transit, driving alone, but not carpooling. By *(ii)* we assume that the trips from the RPC would not have been carpooled without the platforms. That is, carpooling platforms are not formalizing existing informal carpooling.

According to the statistics from Brutel and Pages [100] (INSEE), in France, car trips are predominant even for small travel distances. If we take only distance into account, based on these statistics, we estimated that at least 95% of the trips of the RPC would have been made by driving alone. However, this first rough estimate of modal shift from carpooling platforms should be carefully taken since it is based on global statistics, whereas the RPC is a small sample corresponding to a particular population (it has chosen to carpool, which is not common).

To further investigate the question of modal shift effects, we computed realistic travel times for each carpooled trip and for all alternative transportation modes based on the actual road and public transit networks (see Appendix A). Our results on travel time confirm that the modal shift due to existing regular carpooling platforms should be almost exclusively from driving alone to carpooling.

To confirm previous results, we imagined a counterfactual scenario maximizing the use of transportation modes other than cars. More precisely, in this scenario, each traveler would have chosen, by descending priority:

- if the itinerary by bike is less than 30 minutes, the traveler chooses the bike or walks, also called soft mode;
- if the itinerary by public transport is less than 1 hour, the traveler chooses public transport;
- if no itinerary meets the above conditions, the traveler drives alone.

Even with such extreme choices driving alone is still the predominant alternative to carpooling for the trips of the RPC (Table 1 shows the results for Isère and Loire-Atlantique).

We can conclude from this preliminary work that, when assuming *(i)* and *(ii)*, driving alone is a valid primary alternative for existing trips made using regular carpooling platforms. To properly evaluate existing modal shift effects, we plan to lift assumptions *(i)* and *(ii)* by including informal carpooling and no trip in the alternatives and using refined choice models (e.g., multinomial models). Nevertheless, how current estimates of modal shift effects due to regular carpooling platforms inform us about modal shift effects in the future remains an open question.

Table 1: Counterfactual with conditional choice model modal share results)

	Isère	Loire-Atlantique
car (%)	69.0	62.6
pt (%)	23.7	8.4
soft (%)	7.3	28.9

4.6 Preliminary conclusions and future work

In France, the mileage corresponding to regular carpooling using digital platforms is estimated at 26,329,726 km for 2021, according to the RPC. An optimistic estimate of the emissions avoided by regular carpooling platforms can be computed by assuming that the users would have driven alone without these platforms: based on the emission factor from ADEME (192 gCO_2e/km by car, with an uncertainty of 20%), we obtain 5056±1027 tCO_2. As explained in previous sections, this value could be refined by taking into account the structural effects of carpooling (and in particular modal shift effects) and the direct impacts of the ICT infrastructure.

4.6.1 Current avoided emissions due to regular carpooling platforms compared to global GHG mitigation scenarios. Let us consider four GHG emissions reductions strategies at the scale of France: the Stratégie Nationale Bas Carbone (SNBC) [10], the ADEME's *Transition(s) 2050* [8], the Plan de Transformation de l'Économie Française (PTEF) [101] and the negaWatt scenario [9]. All these strategies come from grey literature and have for objective to reach the net-zero emissions in 2050, in coherence with the Paris Agreement.

To reach global GHG objectives, all these scenarios rely at least on three types of levers for mobility, summarized by The Shift Project [101]:

- decrease in the number of trips (sufficiency)
- modal shift from driving alone to soft and shared modes
- increase in the efficiency of the vehicles (efficiency).

The negaWatt's scenario expectations are also based on tighter speed limits. Increasing carpooling is expected to be a lever of the second type and is often represented by its effect on the average occupancy rate of vehicles. For example, in the four scenarios of *Transitions(s) 2050* to reach carbon neutrality in 2050 (from the more restrictive to the more technooptimistic), the rise in occupancy rate accounts from 1% to 14% of carbon footprint diminution.

France instantiates the Paris Agreement in the Stratégie Nationale Bas Carbone (SNBC). Among the four documents listed, SNBC is the only strategy that contains quantitative and possibly restrictive goals per phase. In the SNBC, the yearly carbon budget for transport between 2019 and 2023 is 128 Mt, the goal being 112 between 2024 and 2028. To reach this goal, we need GHG emissions reductions of 2.5% or 3.2 Mt every year. Given our preliminary estimates of 5056±1027 tCO_2, the emissions avoided by regular carpooling platforms represent only 1.6% of the required yearly emissions reductions for transportation. Note that GHG emissions reduction objectives have been defined based on an assessment of the current situation, which already takes currently avoided emissions into account. In that sense, only additional avoided emissions matter with respect to the 3.2 Mt of reduction required every year. Still, the comparison between currently avoided emissions and goals related to carpooling illustrates the magnitude of the task ahead. Such a modest contribution of carpooling platforms compared to GHG mitigation needs is, of course, not surprising given that regular carpooling organized via digital platforms is not so widespread. Both PTEF and *Transitions(s) 2050* note that current strategies to develop carpooling are ineffective. The question of its potential is, therefore, still relevant.

4.6.2 The future contribution of regular carpooling platforms to global GHG mitigation scenarios. Two conditions must be satisfied to make regular carpooling platforms an effective means of GHG emissions mitigation. First, obstacles to carpooling must be lifted such that it comes to represent a substantial fraction of mobility. Second, and crucially, negative structural effects that may offset potential gains from a large-scale development of carpooling must remain limited.

Obstacles to carpooling and lockins have been discussed in Section 4.3. Some of the global scenarios for France propose strategies to address them. These include: focusing on commutes between homes and companies (*PTEF*), relying on local initiatives from citizens and associations, public policies, financial incentives, reserved lanes for carpooling, and dynamic ridesharing supported by autonomous vehicles (*Transitions(s) 2050*). That said, a systematic review of how such measures could tackle the specific obstacles listed in Section 4.3 would be useful. We are particularly interested in investigating travel behaviors such as activity chains, which make it logistically rather than psychologically difficult to carpool. This obstacle seems to be overlooked by the proposed strategies.

Negative structural effects that may offset potential gains due to regular carpooling platforms have been discussed in Section 4.3. This remains a largely open problem. Because structural effects are expected to be mostly negative, our current strategy is to only consider modal shifts and try to estimate whether the potential of carpooling platforms is, in this case, significant compared to global GHG mitigation scenarios. If that is not the case, then taking other structural effects into account is unlikely to improve the potential of carpooling platforms.

5 CONCLUSION

In this paper, we have underlined what we consider to be frequent and problematic shortcomings in the state of the art of evaluation of digital technologies for GHG emissions mitigation. The conclusions presented here are still preliminary, and a more exhaustive review of the state of the art is needed. The guidelines that we propose also need to be refined into a structured methodology, which we intend to apply to our case study on carpooling.

Finally, let us emphasize the importance of the question addressed in this paper. Claims about the benefits of using digital technologies for GHG emissions mitigation form the basis of many arguments against the regulation of the ICT sector and in favor of increased spending in research and development in that field. Being able to identify as early as possible whether these claims are justified or empty promises is key to making informed decisions about our strategy to tackle climate change.

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A RIDESHARING STUDY

A.1 Software and data

To make the experiments as reproducible as possible, we base our study only on publicly available data and open-source software. We present below our data and software.

First, transport demand data come from the *Registre de Preuves de Covoiturage* (RPC) [35]. This database provides practically all, if not all, the regular carpooling journeys performed with digital carpooling platforms for each administrative region in France. It is open and anonymized: geographical coordinates are rounded, introducing additional uncertainties, and unique journeys are deleted. This raises an issue because the coverage brought by the regular carpooling platforms is currently limited. Indeed, there are an average of 1, 56 million daily travels in 2019–2020 in the Métropole de Grenoble [102]. In contrast, the regular carpooling considered in the RPC only lists trips for 24.16 travelers per day on average in the same area. The evaluation of GHG emissions currently avoided should therefore be seen as one of the first steps towards a thorough evaluation of the potential of carpooling.

Second, we use the open-source GraphHopper [103] journey planner to compute the travel times and distances of each journey. We have noticed a maximum variation of 16 min (corresponding to 20% of the total duration) in Isère (RPC, October 2021) between journey durations calculated by GraphHopper (without traffic) and by Google API (with traffic). However, computing all the journey durations while including traffic or using Google API would require too much computing resource and/or time, so we decided to stick to GraphHopper and OSM data without traffic. This constitutes another source of uncertainty in our computations.

Third, the transport supply data – roads and public transport – come from OpenStreetMap contributors [104] and from the *French Point d'Accès National* (PAN) [105] respectively.

Fourth, the GHG emissions factors come from ADEME [45]. The calculation of the avoided GHG emissions is based on the traveled distance and the impact factor for each vehicle. We take into account only the emissions related to the consumed fuel (i.e., we ignore GHG emissions due to the production of the vehicles). Several uncertainties are associated to these data: (i) the emission factors are average over several types of vehicles (typically 60% for most types of vehicles [45]); (ii) for public transportation, there are assumptions about the number of passengers while in fact the number of passengers can change between lines.

The uncertainties associated with the GHG emissions factor are the only uncertainty we take into account numerically. Taking into account all other aforementioned sources of uncertainties is still a work in progress.

Finally, we used Python to process the data and generate the visualizations. The code used is available on https://purl.archive.org/rasoldier.limits2022.

A.2 Data analysis

We only considered the journeys completed in October 2021 in the administrative departments of Isère (2, 225 travelers) and Loire-Atlantique (9, 935 travelers). These two departments are far apart and different in terms of total population (1, 271 millions for Isère and 1, 429 for Loire-Atlantique) and geography (mountains and valleys in Isère and coastal plains in Loire-Atlantique). Figure 1 represents the journeys (the *mobility needs*) for the administrative area Isère that are in the scope of our study (October 2021).

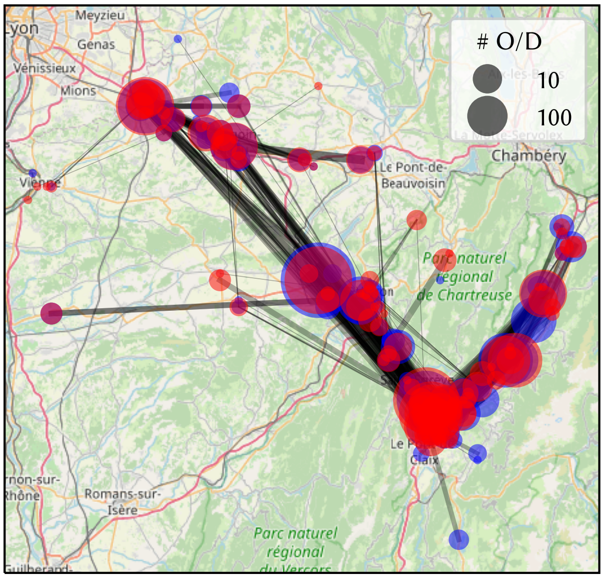


Figure 1: Journeys from RPC per traveler in Isère during October 2021. Area of circles are proportional to the number of trips coming from (blue) and to (red) its center

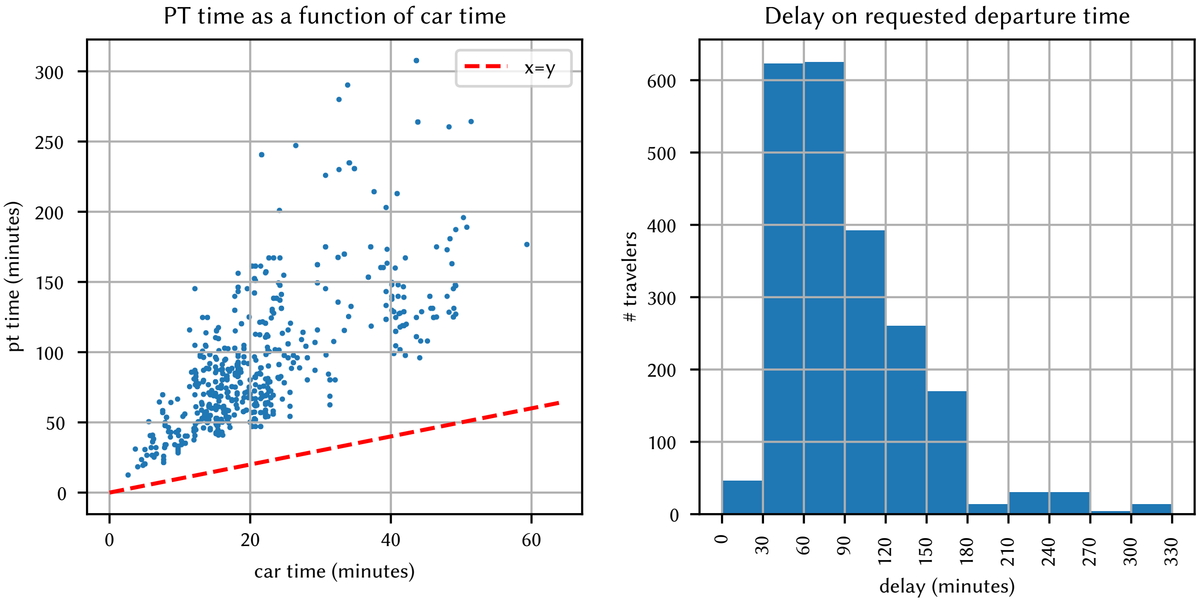
Figure 2-left depicts the the travel time differences between public transportation ("pt time") and carpooling ("car time") for both departments. Each point corresponds to one travel, and the red dotted line is the unit slope diagonal. This figure shows that carpooling is always more efficient in terms of travel time than public transportation.

As explained in Appendix A.1, taking into account the traffic congestion (computed with Google Maps) would result in car trips being 16 minutes longer. This would shift the two scatter plots in Figure 2-left by 16 minutes to the right. As a consequence, a few trips would be shorter in public transportation than by car. However, this would not change the result for the conditional model, since car trip time is not an input in this mode choice model ("car" is the default value).

Figure 2-right depicts the distribution of the delay after the requested departure time for the travelers, again for both departments. This figure shows that, for most travelers, the delay is more than one hour after the requested departure time.

In Table 1, we notice that in Loire-Atlantique, the "soft" travel modes are more used than public transportation, whereas the conditional model predicts the opposite trend for Isère. This difference is coherent with the fact that trips in Isère have, in appearance, shorter alternatives in public transportation than in Loire-Atlantique (see Figure 2). However, the number of samples (2, 225 in Isère vs. 9, 935 in Loire-Atlantique) can explain this difference as a statistical artifact, so no conclusion is possible here.

(a) Isère



(b) Loire-Atlantique

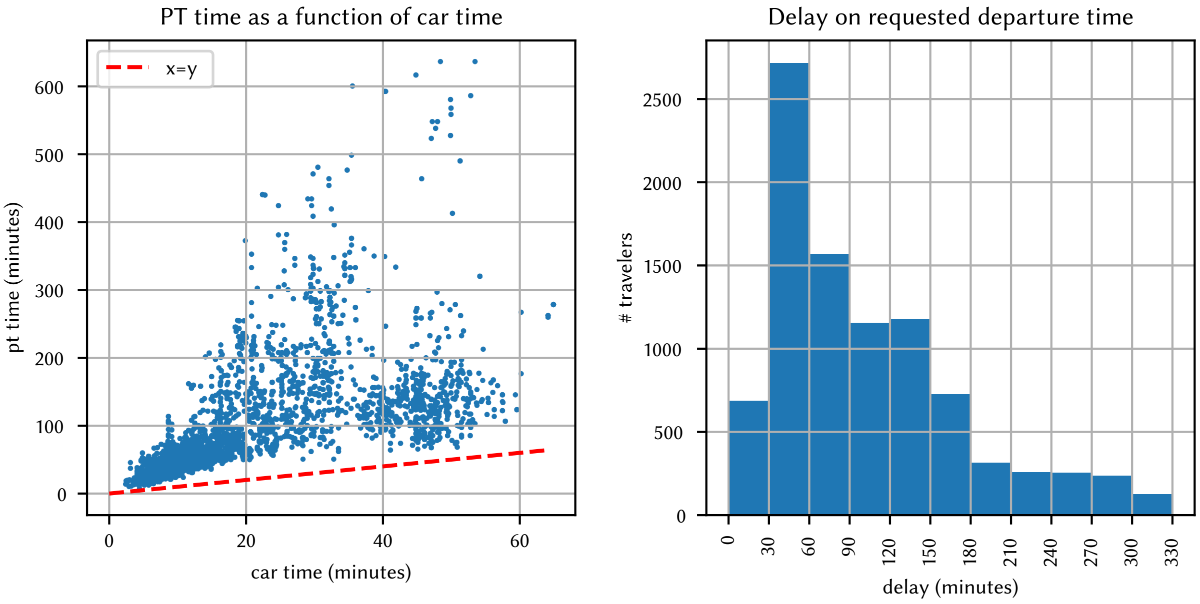


Figure 2: Comparison of PT (public transportation) time and car time for RPC journeys in Isère and Loire-Atlantique