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1 **ASSESSING THE IMPACT OF MONETARY INCENTIVES FOR WALKING USING**
2 **AGENT-BASED MOBILITY SIMULATIONS AND DISCRETE MODE CHOICE**
3 **MODELS**

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1 **ABSTRACT**

2 Sustainable and active urban mobility options, such as walking, represent a significant opportunity
3 for achieving environmentally friendly and healthier transportation in the Paris Region. Despite
4 the well-known benefits of walking on mental and physical health, there is a need to substantiate
5 the potential gains that could be brought by supporting the development of walking as a transport
6 mode in the eyes of public authorities at different governmental levels. Our research aims to
7 analyze and model the potential impacts of economic incentives on walking behavior in the Paris
8 Region. We do so by addressing the research problem of how these strategies can effectively
9 encourage individuals to choose walking as a mode of transportation. Also, we look at how the
10 modal shift would impact the use of Public Transport (PT), walking, bike, and private car. We
11 propose to tackle the topic through a quantitative modeling exercise where the impact of financial
12 incentives for walking is assessed in detail by using agent-based modeling and simulations of
13 36 different incentive scenarios. In our simulations, travelers' behavior is modeled and considered
14 individually, and a mode choice model is used to approximate real-life user decision-making. Such
15 a model takes into account different components of a trip, such as duration and cost. In this work,
16 a representative simulation of the *Île de France* area and the underlying mode choice model are
17 extended to test the incentive policies for walking. Various incentive scenarios are studied, and,
18 by integrating the incentives in the mode choice model, we can assess each scenario's impact
19 on user decisions. This study sheds light on potential strategies that decision-makers and other
20 stakeholders in the region's ecosystem could take to achieve multisectoral sustainable goals using
21 economic incentives for walking to encourage more sustainable mobility.

22

23 *Keywords:* pedestrian mobility, modal shift, agent-base simulations, discrete mode choice, active
24 mobility, sustainable mobility

1 INTRODUCTION

2 Transport decarbonization is one of the main goals of governments and societies aiming to tackle
3 the climate crisis resulting from the transgression of planetary boundaries. The European Com-
4 mission has focused on developing policies to ensure achieving and maintaining the quality of life
5 and a well-being economy while respecting the planetary boundaries. (1) forewarned about the
6 impacts of social and economic systems on the outstepping of these boundaries that restrict the
7 “safe operating space for humanity”. In complex urban ecosystems, mobility is one of the proxies
8 for individual, social, and economic activities enabling human development and well-being. How-
9 ever, it also represents one of the primary sources of pollutant emissions impacting the health of
10 living beings and the natural environment. Therefore, identifying potential pathways towards sus-
11 tainable mobility and addressing the barriers to encouraging decarbonized transportation is a way
12 to tackle some of the existing challenges of complex sociotechnical systems (2). Active modes,
13 such as walking and biking, represent a driver towards transport decarbonization and an oppor-
14 tunity to address diverse multisectoral challenges in relevant social and economic sectors such as
15 transportation, health, and land use.

16 **Transitioning towards more sustainable mobility**

17 Sustainable mobility transitions require targeted strategies considering the specificities of territo-
18 ries, government echelons, and complex ecosystems of actors such as the ones involved in urban
19 mobility. Therefore, the shifts necessary to attain more sustainable mobility practices depend on a
20 mix of individual, social, physical, and economic conditions, as described in (3). Addressing and
21 encouraging pedestrian mobility as a lever for sustainability requires a system’s perspective taking
22 into account the cultural aspects of the social dimension. (4) identified the multiple cultural ele-
23 ments behind the potential incentives and penalties that need to be considered to have an effective
24 impact in promoting modal shifts and motivating new mobility practices (E.g., social connotation
25 or judgment of people needing to walk, or from the stakeholder perspective, walking as an evident
26 mode that does not require investment nor much extra attention and that does not bring a significant
27 Return on Investment).

28 **Appraising Walking**

29 Walking is considered the “stem cell of mobility” (5). It is also an essential element supporting the
30 achievement of local, regional metropolitan and national policies and goals. Walking should mobi-
31 lize transversal cooperation of different levels of government and actors, shaping policies apprais-
32 ing centrality and proximity as illustrated in the 15-minute city concept (6). Appraising centrality
33 and increasing the attractiveness of this model could represent a lever to encourage people to walk
34 and cycle, increasing the distances traveled in these modes while at the same time reducing the use
35 of individual motor vehicles. The link between the built environment and the social relationships
36 and exchanges (that are practices happening in public spaces, enabled by walking sometimes) was
37 identified and discussed in (7) and in (8). In this sense, (9) also contributed by proving there is a
38 positive correlation between the “comfort of walking and recreational well-being, happiness, and
39 life satisfaction”, based on findings in (10). Nevertheless, walking tends to be left out as a criti-
40 cal piece of the mobility system since the servitization of walking is potentially undesirable and
41 seems hardly achievable (11). Another reason why walking is more than relevant to achieve sus-
42 tainability is health as the present and diverse urban-related lifestyles have a big impact on health.
43 For example, the super processed food available for consumption mostly in urban cores, and the

1 way we move or don't move at all (sedentariness) on a daily basis. The lack of physical activ-
2 ity appears to be the cause of at least 7.2% of all-cause deaths and 7.6% of CVDs related deaths
3 worldwide (12). Just in 2017, in Île de France, circulatory diseases were one of the first causes of
4 death, provoking around 254 deaths for every 100,000 inhabitants (13). This problem did not go
5 unnoticed since, at a national level in France, the Public Health Code (Article L1172-1) integrates
6 the possibility for general practitioners to propose adapted physical activity medical prescriptions
7 (fr. *Activité physique adaptée*, APA). This prescription is given for three to six months and provides
8 individuals with the opportunity to adopt healthier habits by including physical activities in their
9 daily routines and having medical supervision and advice to do so.

10 **Incentives for Behavior Change**

11 One of the main barriers to encouraging walking is the lack of a straightforward industry behind
12 it (14). Unlike the bicycle, walking requires no other vehicle than one's own feet. This research
13 explores economic incentives, which seem to have more impact when applied in parallel with other
14 non-economic incentives, as described in (15). Policies aiming to incentivize virtuous behavior,
15 such as walking, can be classified according to their type of interventions, and expected functions.
16 The functions of these policies can be multiple, as illustrated by (16). The authors considered
17 functions linked to skills, finances, access, aesthetics, safety, convenience, space, and awareness.
18 All of which can have gain or loss effects according to the objectives and implementation strate-
19 gies. (17) discuss the concept of "economic incentives," which encompasses a broad range of
20 actions aimed at motivating individuals. These incentives can take various forms: "cash payments,
21 lotteries, coupons for discounted or free goods and services, gifts, free or reduced-price medical
22 services, and the chance to elude disincentives". (18) explored the effectiveness of financial incen-
23 tives for a pedometer-based walking promotion program among almost 17 000 individuals aged
24 40-75 years in the city of Takaishi, Japan, between 2016-2018. The authors set particular focus
25 on the link between health-related costs and economic incentives based on the daily step count.
26 The main results displayed a correlation between the participation in the study and the reduction
27 of health expenses in a year within the sample of Takaishi inhabitants: "The average medical costs
28 per year was JPY 85,525.8 for the walking group and JPY 152,602.8 for the control group." "In
29 fact, there was a difference of 67,077 yen in the average medical cost per person per year between
30 the walking and control groups. With 1,923 walking group participants, the total medical cost
31 reduction was predicted to be at least 12,898,904 yen (around 83 000 €). Similarly, in Australia,
32 a study conducted by Victoria Walks in Melbourne, found that investing in walking yields signifi-
33 cant benefits in terms of decongestion, environmental improvements, and health. The study found
34 that for every dollar invested in walking initiatives in infrastructure or communication campaigns,
35 approximately 13 dollars return in benefits (19).

36 **BACKGROUND**

37 In this work, we propose a novel approach to assessing the impact of financial incentives. Our
38 approach relies on the use of agent-based simulation of mobility. Such a simulation individually
39 considers every traveller (called agents), with related activities and trips. Global phenomena such
40 as congestion emerge from local interactions between the agents. Using a behavioural model for
41 agent decisions, the mobility-related decisions of travellers can be dynamic and depend on the
42 quality of each alternative. This allows us to assess the impacts of a change on the mobility offer
43 side on traveller decisions. We address this by testing the impacts that monetary incentives for

1 walking could have on mobility in the Paris region and by responding to the following research
2 question:

3 *How can walking be incentivized to enable behavior change towards more sustainable*
4 *mobility?*

5 To do so, we focus on walking and delve into the potential financing schemes for incentives
6 for pedestrian mobility as well as the global effects in terms of modal shifts and mobility practices.

7 **France's Active Mobility Context**

8 At a national level, in France, around 18 million people commute (home to work) by means of their
9 private car, disregarding the distance traveled. Factually, 60% of employed people travel less than 5
10 km using their private vehicle. In Île de France, even for short trips, cars represent not the first, but
11 an omnipresent mobility option in the decisional panel of individuals. In contrast, only 8% travel
12 by active modes for their daily commute trips, and 2% walk (20). Also, in the Paris region, walking
13 represents 40% of the trips made in a day, and in the case of the city of Paris, the numbers go up to
14 more than 50%. Whether it is to encourage more people to walk or to provide better tools to people
15 that are already walking (sometimes constrained to do so), the encouragement of walking has been
16 identified to be of great relevance. Additionally, speaking of walking is also speaking about equity
17 and accessibility. For example, in 2008, people with severely reduced mobility represented 12% of
18 the population in the region, according to the *Handicap-santé* survey. Moreover, the ageing of the
19 population also touches on the issue of accessibility. In the Paris region, 14,7% of the population is
20 65 years and older, and the representation of this group of age is projected to continue to augment.

21 **METHODS**

22 **Simulation Model**

23 In our work, we use the MATSim simulation framework (21). MATSim is a fully open-source tool
24 in constant evolution with an extended community supporting it.

25 The main input for an agent-based mobility simulation, besides the road network, is the
26 mobility demand. In MATSim this is referred to as the *population*. Each traveller in MATSim is
27 modelled as a separate *agent*. MATSim is *activity*-based in the sense that each agent has a sequence
28 of activities to perform throughout the simulated period (typically one day). These activities are
29 located in space and in time, consequently an agent needs to travel in order to perform the activities.
30 For each trip between two consecutive activities, the agents can use one of the modes available in
31 the simulation. The activities and the travel routes between them constitute the agent *plan*.

32 Alongside the network and the population, other inputs can be supplied to MATSim ac-
33 cording to the user's needs. MATSim is built in a modular manner which allowed the community
34 to contribute with various extensions adding features to the tool. It is possible to simulate Public
35 Transport (PT) systems by supplying a MATSim transit schedule specifying the stops, lines and
36 departure times. A tool for converting a PT schedule in the GTFS format to a MATSim transit
37 schedule is provided alongside MATSim.

38 The simulation consists in running all the agent plans, i.e. travelling between activities
39 using the indicated modes and following the indicated routes. Some travel modes (car, PT, MoD)
40 involve using a vehicle that travels throughout the links of the network while trips of other modes
41 are simply teleported because they are assumed to not generate any congestion (walk and bike).

42 MATSim's key feature is certainly the replanning step and the iterative manner in which
43 simulations take place. This allows agents to change their plans according to observed performance

1 in previous iterations in order to build better plans on the individual level. Consequently, the
 2 changes in agent plans at the end of the simulation reflect the impact of the mobility offer on the
 3 user choices.

4 The performance of an agent plan depends on other agents' plans. For instance, the travel
 5 time of a car trip depends on the congestion on the route which in turn depends on the num-
 6 ber of travellers on the route. In order to prevent oscillation effects in the plans, not all agents
 7 should perform replanning at every iteration. Consequently, a certain proportion (usually 5%) of
 8 the population is randomly selected at the beginning of every iteration for replanning. The other
 9 agents carry on with the same plans. Consequently, several iterations are needed to reach system
 10 equilibrium.

11 An approach for agent plans replanning that relies on Discrete Mode Choice (DMC) models
 12 has been proposed into MATSim Hörl et al. (22). This approach exclusively focuses on choosing
 13 the transport modes for the trips. When an agent is selected for replanning, its journey through
 14 the simulation is divided in tours that start and end at a *home* activity. E.g. a sequence home →
 15 school → shop → leisure → home → leisure → home is divided into two tours: home → school →
 16 shop → leisure → home and home → leisure → home. Afterwards, and for each tour, all the mode
 17 sequence alternatives are considered. A first filtering is performed to filter-out the alternatives that
 18 violate the pre-evaluation constraints (e.g. taking car without possessing a license). Then, utilities
 19 are computed for each tour alternative as the sum of utilities of its trips as illustrated in Figure
 20 ???. The utility of a trip depends on the considered mode but generally involves computing the
 21 trip route and estimating travel time, wait time and cost. Each mode m is then associated with a
 22 utility function $U_m(\chi)$ where χ denotes the trip that is evaluated. Each utility function is a weighted
 23 sum of the relevant trip components and the mode-specific constant. A second filtering takes place
 24 to rule-out tour candidates that violate post-evaluation constraints (e.g. utility below a certain
 25 threshold or a PT trip route that only consists in walking). Among the remaining candidates, one
 26 is chosen using a selection method based on the estimated utility. The most often used method is
 27 the Multinomial Logit selection Train (23).

28 Using the DMC model approach described above, calibration is made easier by focusing
 29 only on the transport modes and filtering out "bad" plans beforehand, only acceptable plans are
 30 simulated. This reduces the number of iterations that is needed to reach the equilibrium.

31 For our study, we rely on a well-established methodology for the generation of a synthetic
 32 population for the Île-de-France. First introduced in ??, the tool is openly available online and relies
 33 on various socio-economic data. The openness of the data and the approach make the simulations
 34 fully reproducible and extensible by the research community. At a 100% sampling scale, the
 35 resulting population consists of more than 5 million households with 11 million persons and 46
 36 million individual daily activities. The parameters of the discrete mode choice model that is used
 37 are calibrated so that a simulation with the real-life mobility offer reproduces the same high-level
 38 use mode choices.

39 **Implementing monetary incentives in the DMC model**

40 In this work, the DMC model has been extended to support the incentive scenarios that are consid-
 41 ered. We note τ the incentive amount per kilometer. The incentives are integrated in the utilities
 42 of incentivized trips using the same utilitarian value of money, noted as β_{cost} that is already used
 43 in U_{car} and U_{pt} to take into account the costs of car and public transport trips ($\beta_{cost} < 0$). More
 44 precisely, the utility function for trips with modes walk, PT, and car have been extended:

1 The utility function of walked trips $U_{walk}(\chi)$ is extended with a term representing the in-
 2 centive money that the traveler would receive if the trip is performed. It is computed on the basis
 3 of the distance to walk in kilometers $\chi_{distance}$ and τ :

$$U'_{walk}(\chi) = U_{walk}(\chi) - \beta_{cost} \cdot \tau \cdot \chi_{distance} \quad (1)$$

4

5 With $\beta_{cost} < 0$ and $\tau > 0$, subtracting the extra term integrates the incentives positively in the utility
 6 ($U_{walk}(\chi) \leq U'_{walk}(\chi)$)

7 The utility function of public transport trips $U_{pt}(\chi)$ is extended with a term similar to the
 8 previous one. Except that the considered distance is the distance that is walked by the user along
 9 the trip as an access to, egress from and transfer between public transports.

$$U'_{pt}(\chi) = U_{pt}(\chi) - \beta_{cost} \cdot \tau \cdot \chi_{walkedDistance} \quad (2)$$

10

11 E.g., with the $\tau = 0.5\text{€}/\text{km}$, if the trip consists of a 1km walk to a bus station, then taking the bus
 12 until bus station A, then walking 200 meters for train station B then taking the until station C then
 13 walking 1km to the final destination, the incentive amount is 1.1€. This new term opposes the
 14 base cost of the public transport trip.

15 Finally, the utility function of car trips $U_{car}(\chi)$ is extended with a term reflecting the extra
 16 cost for travelling with cars due to financing the penalties.

$$U'_{car}(\chi) = U_{car}(\chi) + \beta_{cost} \cdot \bar{\tau}_i \cdot \chi_{distance} \quad (3)$$

17

18 The extra cost per kilometer $\bar{\tau}_i$ is updated at the end of each iteration i by dividing the total amount
 19 of paid incentives on the total distance driven by cars during that iteration. With $\bar{\tau}_i \leq 0$, the extra
 20 term has a negative impact on the utility ($U_{car}(\chi) \geq U'_{car}(\chi)$) and adds up with initial cost of the
 21 car trip. This term is activated only when the ‘‘Polluter Pays’’ principle is followed.

22 During the simulation, the impacts of the incentives is achieved gradually as only a fraction
 23 of the synthetic population (5%) is allowed to perform mode choice and potentially make changes
 24 on their mobility plans. This ensure smooth transitions and convergence to an equilibrium.

25 EXPERIMENT

26 We describe in this section the incentive scenarios that are investigated in this work.

27 In this study, We consider three dimensions to the monetary incentives for walking. The
 28 first is the incentive amount in €/km that constitutes the basis on which the incentive received by
 29 the traveller for a trip is computed. 6 incentive amounts were investigated in this study: 0.1, 0.2,
 30 0.5, 1, 1.5 and 2€/km. This value corresponds to the τ parameter defined above.

31 The second dimension is what we call the incentive policy, it defines which walked trips
 32 are incentivized. Three incentive policies are investigated: (i) incentivizing only fully walked
 33 trips, with no interaction with another mode. When performing simulations with this policy, the
 34 expression presented in Equation 1 is used. This policy is labelled **W**. (ii) Incentivizing only walks
 35 that are part of a public transport trip, where the user walks to, from and between public trans-
 36 port stations. This policy, labelled **PT**, is enabled in the simulation by the expression presented
 37 in Equation 2. (iii) Incentivizing both fully walked trips and walks related to public transports.
 38 This policy is labelled **WPT** and its simulations are performed by enabling both the expressions

1 described in Equations 1 and 2.

2 Finally, the financing scheme behind providing the incentives is considered. In this work,
3 we distinguish between two schemes: (i) subsidies coming from local authorities, labelled **S** and
4 (ii) applying the "polluter pays" principle under which the cost of the incentives is reflected on
5 car users as an extra cost per kilometer driven. Simulating this scheme is done by enabling the
6 expression presented in Equation 3 for computing the utilities of car trips. This scheme is labelled
7 as **PP**

8 The combination of these incentive dimensions (6 incentive amounts, two incentive policies
9 and two financing schemes) produces a set 36 incentive scenarios. Each scenario is labelled with
10 [amount]-[policy]-[scheme] with each part labelled as described above. E.g. an incentive scenario
11 with an amount of 1€/km, with the **WPT** policy and the **PP** financing scheme is labelled **1-WPT-**
12 **PP**

13 **RESULTS**

14 Simulations of the Île-de-France area with a population scale of 1% have been performed with each
15 if the 36 described incentive scenarios plus no incentive at all for baseline. The population scale is
16 lowered in order to save running times since the number of individual simulated scenarios in this
17 study is relatively high. One simulation on this scale requires around 4 hours and 30 minutes of
18 machine power. The different policy strategies aimed at providing a vision of the potential impacts
19 of diverse policies in terms of incentive amounts provided, or the type of trip being incentivized.
20 Additionally, the results include the impacts of the two different financing schemes: polluter pays
21 and subsidies.

22 The KPIs presented in the previous section have been measured from the simulations and
23 are depicted below. In the graphics, the incentive scenarios are labeled with [amount] + [policy]
24 + [financing scheme]. The [amount] part reflects the incentive amount in €/km (e.g., 1€/km).
25 When the incentive amount is itself an axis on which measures are shown, this part is omitted in
26 the label. The [policy] part reflects the walks that have been incentivized. The policy incentivizing
27 only purely walked trips is noted **W**, the one incentivizing only walks from/to public transport is
28 noted **PT** and the one incentivizing all walks is noted **WPT**. The last part indicates the scheme
29 that is used to finance the incentives: **S** denotes scenarios in which the incentives are supported
30 through subsidies and **PP** denotes scenarios in which the incentives are reflected on car drivers,
31 I.e., polluter pays. For example, the label 1-WPT-S refers to the incentive scenario where all
32 walks are incentivized with an amount of 1€/km and where the incentives are financed through
33 subsidies. The following of this section is structured in this manner: (i) a focus is given to the
34 reaction of the DMC model to the incentives, (ii) the effect of the incentives on the modal shares
35 is outline, (iii) a detailed analysis of the impact of incentives on walking is performed, (iv) the
36 implications on GHG emissions are investigated and (v) the cost of the incentives is outlined (both
37 on local authorities and private car users for "polluter pays" strategies). In the presented results, the
38 KPI values observed in the simulations are scaled back up according to the simulated population
39 sample.

40 **Stability of the mode choice model with the incentives for walk**

41 Before diving into the KPIs themselves, it is necessary to make sure that the DMC model remains
42 stable when the incentives are used. I.e., the traveler behavior reaches an equilibrium, and the total
43 value of incentives converges. Special attention needs to be paid to the "Polluter Pays" effects. As

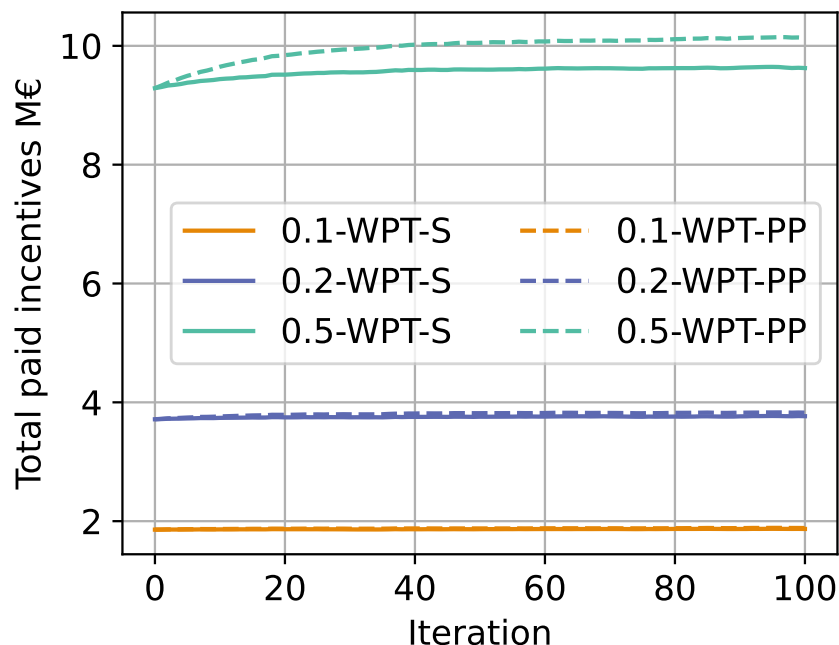


FIGURE 1 Evolution of the total paid incentive during simulations of various incentive strategies

1 more travelers receive incentives, the extra cost per kilometer can increase which reduces further
 2 the use of cars (and thus number of total car kilometers). This then increases the extra cost per
 3 kilometer needed to cover the incentives and might quickly lead, even with low incentive amounts,
 4 to a complete abandonment of cars. This would contradict the goal of funding these incentives
 5 from car users.

6 Figure 1 shows the evolution of the total amount of paid incentives during simulation of
 7 various incentive scenarios. In each setting, this amount converges smoothly during the simula-
 8 tions and doesn't show oscillations. The same smoothness can be observed in the evolution of
 9 mode shares during a simulation of the "1-WPT-PP" incentive scenario (see Figure 2). This is
 10 encouraging for the following of this studies and the use of agent-based simulations and DMC
 11 models for the investigation of monetary incentives in general.

12 **Impacts on modal shares**

13 Figure 3 shows the shares of each mode across the simulated incentive scenarios and incentive
 14 amounts. In general, the incentive strategies that implement the "polluter pays" component are
 15 more effective for discouraging the use of private cars than their counterparts. Moreover, the
 16 incentives for walking towards/from public transports produce a more significant modal shift than
 17 the incentives for walking as a sole mode. Moreover, and as expected, the greater the amount of
 18 the incentives per kilometer, the more the effects of different strategies differ. These differences
 19 can already be noticed with amounts as low as 0.2€/km.

20 With an incentive amount of 1€/km, incentivizing only fully walked trips only reduces
 21 the share of car trips to 34.39% from the initial 35.07%. Its "polluter pays" equivalent achieves a
 22 32.12% of car trips. This is nearly the same effect as the one of the strategy incentivizing only PT-

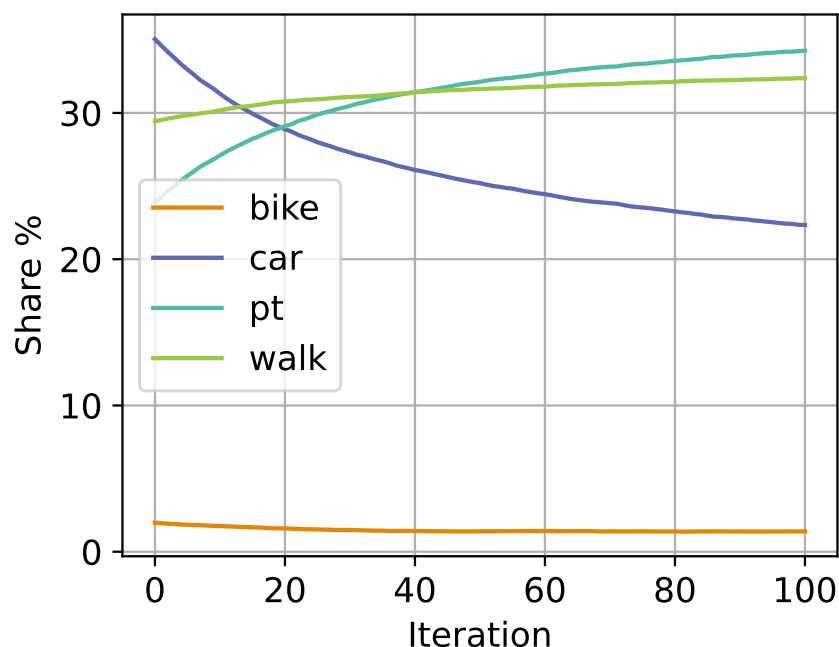


FIGURE 2 Evolution of mode shares during a simulation with the 1-WPT-PP incentive scenario

1 related walks (32.85%). Financing only PT-related walks via car drivers further discourages use
 2 the of cars (29.59%). When incentivizing all walking trips, the share of car trips can be lowered
 3 down to 22.3% thanks to the **WPT-PP** scenario (32.22% with the regular financing scheme).

4 When the incentive amount is increased to 1.5€/km, the share of car trips decreases almost
 5 linearly if the “polluter pays” feature is not used (down to 31% with the **WPT-S**). However, if the
 6 “polluter pays” component is activated, the share of car trips reaches 29.88% if only fully walked
 7 trips are concerned, 22.75% if only PT-related walks are concerned by the incentives, and a critical
 8 value of 2.16% if all walks are incentivized. This shows that both the amount and target of the
 9 incentives can greatly influence the travelling decisions of travelers.

10 Regarding the use of PT, as expected, the incentive strategies targeting PT-related walks
 11 have an effect on the modal share of PT. When incentivizing walked trips only while not activating
 12 the “Polluter pays” component, the shares of PT trips slowly decreases as the incentive amount
 13 increases. However, with “Polluter pays”, PT gains travelers even though the incentive does not
 14 directly encourage this mode. This can be explained by the extra cost of using cars that encourages
 15 travelers to switch to public transports. This can be seen in Figure 28 where the shares of Public
 16 Transport trips according to trip distance are compared across the “No incentive”, **1-W-S** and **1-W-**
 17 **PP** scenarios. The extra cost on the use of car majorly allows to shift long trips to public transport.
 18 Figure 27 Shares of each mode across each of the simulated incentive scenarios

19 As for walking as a main mode of travel, incentivizing only such trips produces the highest
 20 shares for this mode regardless of the use of “polluter pays” or not. However, under 1.5€/km
 21 of incentive, while the incentive of PT-related walks only lowers the part of fully walked trips.
 22 Its “polluter pays” counterpart is able to encourage this mode. Finally, for the bike mode, even
 23 though it is not directly concerned by any of the incentive strategies, its use is greatly impacted. In

1 most of the simulated incentive strategies, the share of bike trips lowers as the incentive amount
 2 increases. In some cases, however with high incentive amounts (**PT-PP** and **WPT-PP**), the use of
 3 bikes increases.

4 **A focus on the impact of incentives on walked distances**

5 Figure 29 shows the walked distances (both total and average per person) observed during sim-
 6 ulations with all the incentive strategies and the incentive amounts considered in this study. In-
 7 terestingly, incentivizing walks only from/to public transports results in more walking than in-
 8 centivizing only fully walked trips. This is essentially thanks to the ability of such incentives to
 9 cause a modal shift for long trips where car can be replaced by public transports thus causing
 10 new intermediary walks. Without any incentive, an average daily walked distance per person of
 11 1.74km/person.day is observed. With an amount of 1€/km, the **W-S** incentive strategy increases
 12 this average to 1.80km/person.day, the **PT-S** strategy to 1.83km/person.day and the **WPT-S** strat-
 13 egy to 1.88km/person.day. The largest impacting incentive feature is however the “Polluter pays”
 14 component. All incentive policies that include this component generate more walked distance
 15 than all the policies that do not. Activating the “Polluter pays” component increases the average
 16 daily person walked distance to 1.88km/person.day, 1.95km/person.day and 2.26km/person.day for
 17 the **W-PP**, **PT-PP**, and **WPT-PP** strategies respectively. Figure 29 Total and average per person
 18 walked distances observed during simulations of the incentive scenarios.

19 Figure 30 shows the distribution of daily walked distances in the simulated populations with
 20 the **1-WPT-S** and **1-WPT-PP** incentive scenarios, each compared to the **No incentive** scenario. We
 21 note that the incentives allow to push the bottom of the distribution (people who walk very little
 22 distances throughout the day) to greater distances.

23 **Impact of the incentives on CO2 emissions**

24 Agent-based mobility simulations allow a fully disaggregated view of the mobility behaviors taking
 25 place during the simulation. These can be aggregated as desired and combined with other data
 26 to obtain more KPIs. One example is the estimation of emissions in the simulation. Figure 31
 27 gives an overview of estimated emissions of CO2 equivalent (combines CO2, methane CH4, and
 28 nitrous oxide N2O) per passenger per kilometer (kg/pkm) as estimated by the ADEME for various
 29 transportation modes (ADEME, 2023). These values were also used in Deliverable 2.4 of the
 30 Anthropolis Chair (Gall, Chouaki, Vallet, 2023).

31 Among the simulation outputs, we find the mode that was used for each trip of each agent
 32 of the simulation as well as the length of the route taken during the trip. Furthermore, if PT is
 33 used, the details on the chain of public transport sub-trips that have been performed can be found,
 34 including the type of PT (train, subway, bus...). This allows to retrieve the passenger kilometers
 35 per each mode, which can then be multiplied by the emission values per mode to estimate the total
 36 emissions of CO2 equivalents for each simulation.

37 Figure 32 shows the CO2 emissions prevented thanks to each of the studied incentive poli-
 38 cies in comparison to the “No incentive” setting. The impact incentives on emissions is analogous
 39 to their impact on walked distances. Incentivizing only fully walked trips saves less emissions
 40 than incentivizing only PT-related walks with 33 tons of saved emissions with the **1-W-S** scenario
 41 against 408 tons with the **1-PT-S** scenario and 432 tons with the **1-WPT-S** scenario. Moreover,
 42 “polluter pays” strategies are able to save much more emissions. The previously mentioned strate-
 43 gies are able to save 619, 1162 and 2417 tons respectively if the incentives are reflected on car

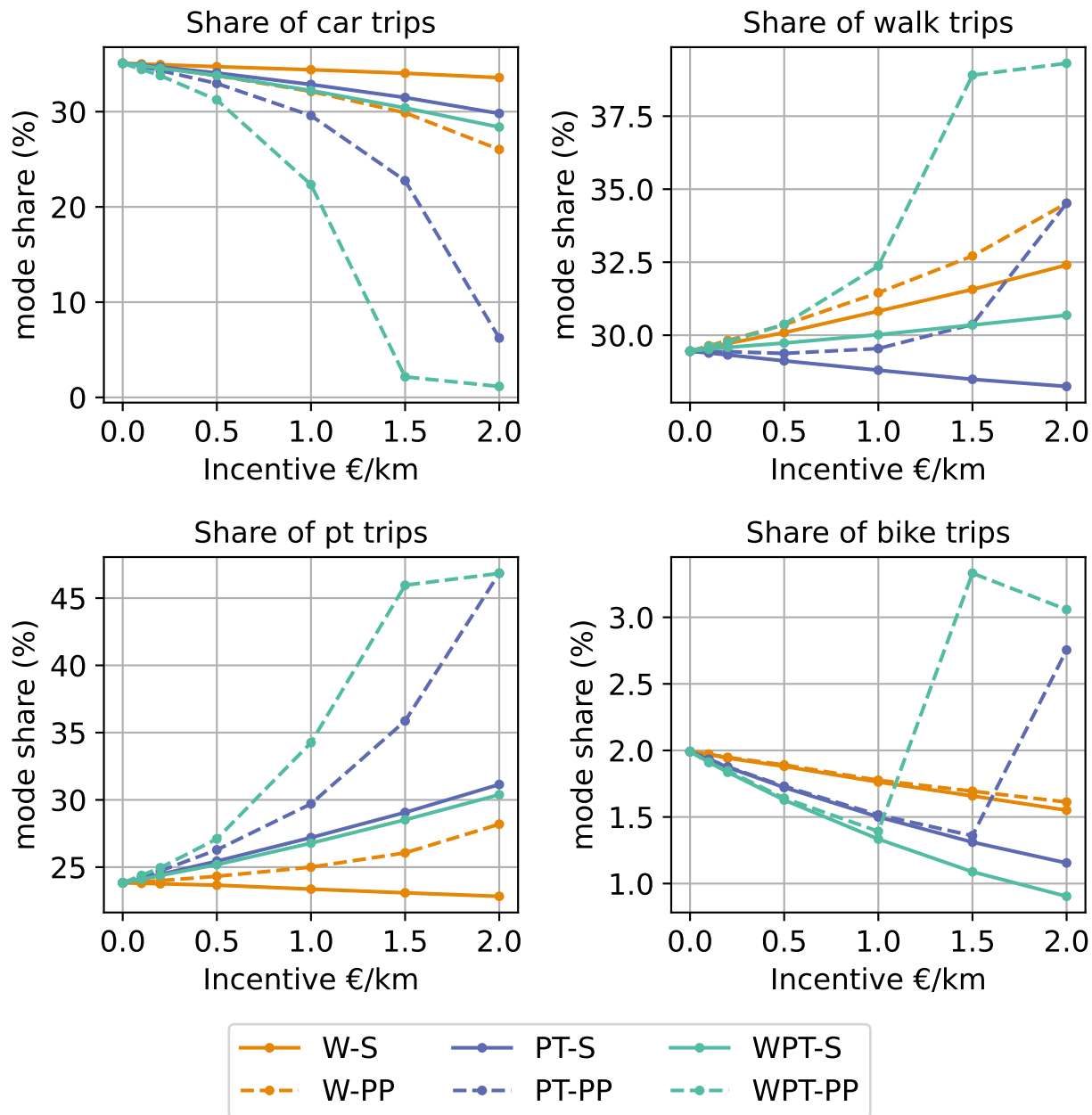


FIGURE 3 Observed mode shares in simulations of various incentive scenarios

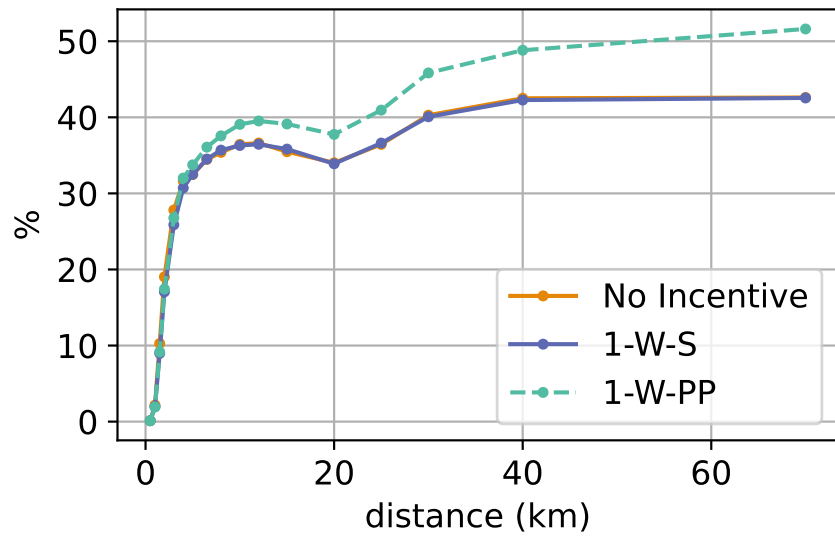


FIGURE 4 Shares of public transport trips according to trip distance in the 1-W-S, 1-W-PP and No Incentive scenarios

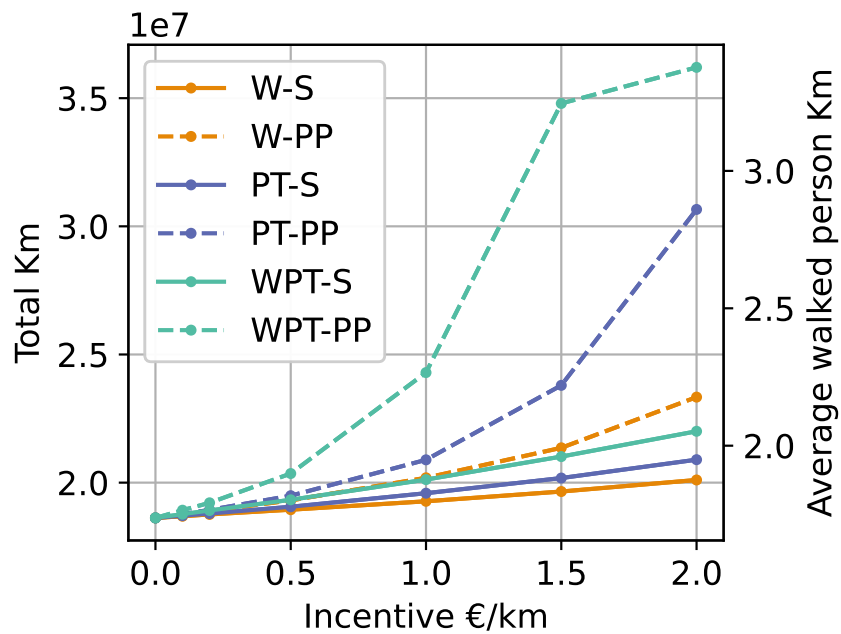


FIGURE 5 Total and average per person walked distances observed during simulations of the incentive scenarios

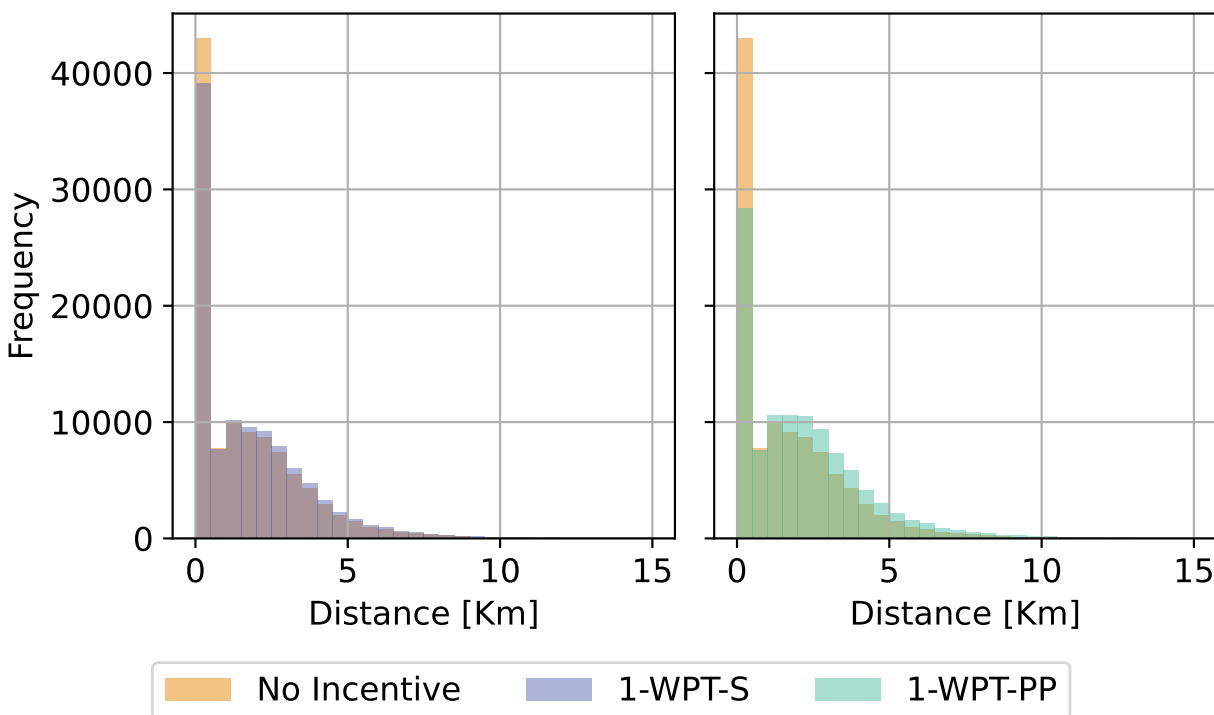


FIGURE 6 Distribution of distances walked per person in the 1-WPT-S and 1-WPT-PP scenarios compared to No Incentive

1 drivers as an extra cost per kilometer. Figure 32 also shows the monetary value of saved CO₂
 2 equivalents. The value of a ton of CO₂ equivalent used to deduce the total amount corresponds to
 3 the value of CO₂ on the EU carbon market (Trading Economics, 2023). At the time during which
 4 the simulation results are analyzed, CO₂ is valued at 91€/ton (as of July 2023). Consequently, in-
 5 centives with 1€/km allow to save between 3K€ and 220K€ depending on the followed incentive
 6 strategy. This analysis allows to put in perspective the effectiveness of the incentives in regard to
 7 their cost. The latter is detailed in the following subsection.

8 Cost implications of incentive strategies

9 The assessment of the impact of monetary incentives for walking cannot be performed without
 10 looking at the cost of supporting such incentives. Our simulation approach allows us to estimate the
 11 impact of incentives on user decisions, thus enabling to retrieve the total amounts of incentive given
 12 to agents in the simulations. Figure 33 shows the total daily incentive amounts paid according to
 13 the incentive strategy (and the incentive amount per kilometer). With the strategies that do not use
 14 the “polluter pays” component, the total amount of incentives is linear in function of the incentive
 15 amount per kilometer, the **1-W-S** scenario results in a total of 10.1M€/day, the **1-PT-S** scenario
 16 10.6M€/day and the **1-WPT-S** strategy in 20M€/day. On the person level, this represents 2.36€,
 17 2.37€ and 2.85€ respectively per day and per person. With the assumption that these incentives
 18 are financed by the local authorities, it is interesting to note that 10M€/day represents 35.74%
 19 of the budget of Île-de-France Mobilités, reported at 10506M€ in 2021 (24). Figure 33. Total
 20 amounts of daily paid incentives in each of the simulated incentive strategies

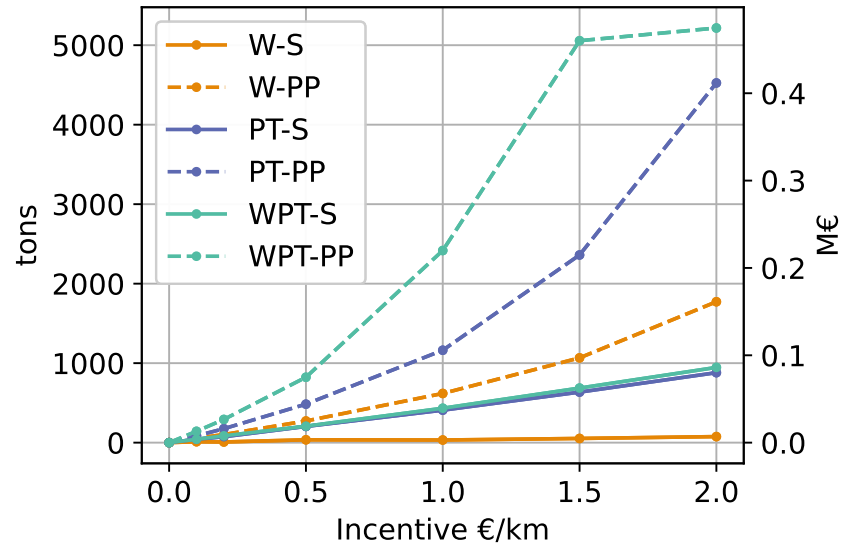


FIGURE 7 Saved CO2 equivalents emissions and their corresponding monetary value in each of the simulated incentive scenarios

Incentive amount	W-PP	PT-PP	WPT-PP
0.1 €/km	0.007 €/km	0,008 €/km	0.015 €/km
0.2 €/km	0.015 €/km	0,016 €/km	0.032 €/km
0.5 €/km	0.040 €/km	0,044 €/km	0.093 €/km
1 €/km	0.091 €	0,116 €/km	0,345 €/km
1.5 €/km	0.160 €	0,302 €/km	7.026 €/km
2 €/km	0.279 €	2,005 €/km	20.625 €/km

TABLE 1 Extra cost for car users to supporting the polluter pays incentives

1 With the implementation of the “polluter pays” scheme, the total amount of incentives
 2 increases and is not linear in function of the amount per kilometer. This is due to the fact that when
 3 the incentive amount increases, so does the extra cost for car users. With 1€/km, using the “polluter
 4 pays” components renders a total of 10.31M€/day with the **1-W-PP** strategy (2.37€/person.day),
 5 10.67M€/day with the **1-PT-PP** strategy (2.42€/person.day) and 24.18M€/day with the **1-WPT-PP**
 6 **PP** strategy (2.99€/day). These incentives being reflected on the users of cars as an extra cost, it is
 7 necessary to investigate the impact of incentive strategies on car drivers. Table 10 shows the extra
 8 cost in €/km necessary to cover the incentives given under each of the studied strategies and the
 9 incentive amounts. The **1-W-PP**, **1-PT-PP** and **1-WPT-PP** incentive strategies imply an extra cost
 10 of 0.091€/km, 0.116€/km and 0.345€/km. With the current cost per kilometer of car used in the
 11 mode choice model being 0.15€/km, this would mean that the cost per kilometer would increase
 12 by up to 230%. Given the non-linear relationship between the incentive amount and the extra cost
 13 per car kilometer, the former needs to be chosen carefully in order to avoid unreasonable extra
 14 costs.

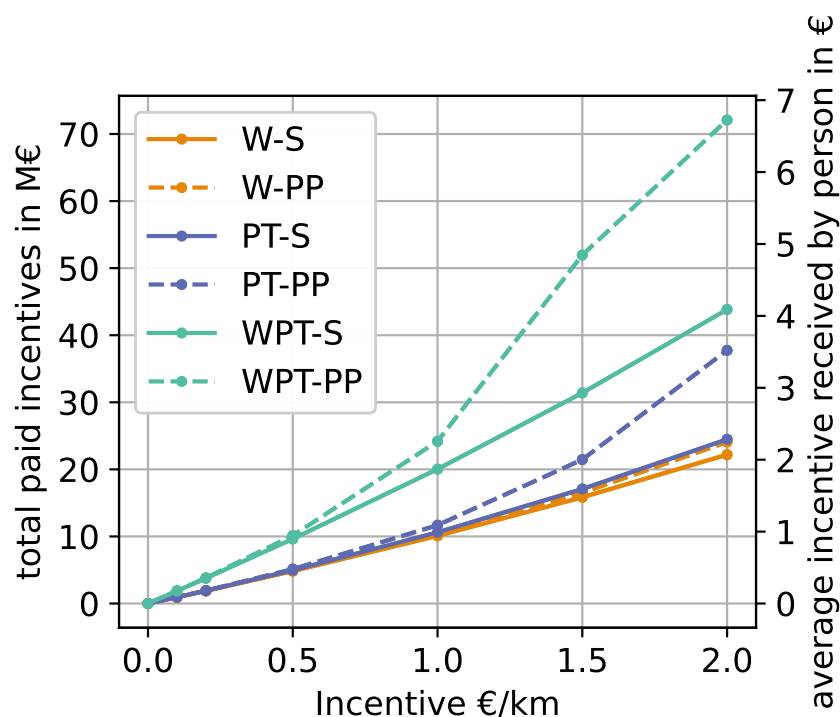


FIGURE 8 Saved CO2 equivalents emissions and their corresponding monetary value in each of the simulated incentive scenarios

1 DISCUSSION

2 The first result of this study is the ability of agent-based simulations and DMC models to enable
 3 the impact assessment of monetary incentives related to mobility behaviours. In this work, the
 4 proposed assessment methodology is applied in the investigation of monetary incentives for walk-
 5 ing. A wide range of incentive scenarios can be implemented and tested within such models. The
 6 incentives are taken into account in the choice model alongside other components such as travel
 7 time and the interplay between the components is considered in the process. The traveler's deci-
 8 sions reach an equilibrium that reflects the impact of the introduced incentives. This is also the
 9 case when in the presence of a feedback loop between the incentives and other components that
 10 are directly dependent on them as illustrated through the "Polluter Pays" financing scheme.

11 Regarding the methodology, many development pathways can be envisioned. The current
 12 state of the DMC implementation does not explicitly forbid very long walks, since the utility of
 13 such trips decreases with the distance making them highly unlikely. However with the incentives,
 14 this can no longer be the case according to the amount per kilometer. This can result in very
 15 long walks that are highly unlikely. Extending the DMC model is then necessary to explicitly
 16 prevent these alternatives. Moreover, the simulation considers that the whole network offers the
 17 same walking potential. This diverges from real-life observations where the layout of the public
 18 space heavily impacts its walkability¹. More efforts ought to be put in this aspect to achieve more
 19 realistic simulations. Finally, the mode choice parameters used in this work are the same for all
 20 individuals in the population, resulting in all travelers reacting similarly to the incentives. Using

¹https://www.driat.ile-de-france.developpement-durable.gouv.fr/IMG/pdf/mep_4__marchabilite_web.pdf

1 a DMC model that is calibrated specifically for different groups of travellers would allow to more
2 precisely assess the impacts that monetary incentives for walking would have (e.g. if the utilitarian
3 value of money is different for car owners and non-owners).

4 In this work, a wide range of incentive scenarios are tested. Each incentive scenario being
5 characterized by an amount per kilometer, the walks that are targeted and whether or not they are
6 supported by an extra cost inflicted on car drivers, an exhaustive study investigation is performed by
7 testing all possible combinations. However, more complex incentive policies ought to be studied:

8 • In this work, only walking is incentivized and bike trips are left out. However, from a
9 policy perspective, active modes are more likely to be incentivized altogether. This will
10 be addressed in future studies.

11 • All the considered incentive policies apply to walks according to the main mode of the
12 trips during which they occur (walk or public transport). In the future incentives that
13 apply only to walks with certain purposes will be tested (e.g. home-work trips).

14 • Besides targeting specific trip purposes, incentives can also be applied only during spe-
15 cific times of the day. For instance, with the objective on reducing the load on pub-
16 lic transport during peak-times, an incentive for fully walked trips can be implemented
17 within that time period to encourage travellers performing short trips to shift from public
18 transports to walking.

19 • It is supposed in this work that the incentive amount received by a traveller is a linear
20 function to the walked distance. Whereas this assumptions already allows to investigate
21 incentive policies and observe their impacts, more complex, and realistic, methods for
22 computing received incentives can be integrated in the DMC model. Such methods do
23 not need to necessarily apply on the trip level, but can span the whole day (e.g. grant
24 incentives up to 1.5€/day only if a person walked at least 500m during the day).

25 • Two financing schemes are investigated in this study, the first supposes that the incentives
26 are provided by subsidies while they are completely reflected on car users in the second.
27 While the latter shows to be more effective for encouraging a modal shift towards walking
28 and public transports, it often comes at prohibitive extra costs for using cars. Exploring
29 intermediate schemes where only a fraction of the incentives cost is reflected on car
30 users can reveal configurations where the advantages are preserved while mitigating the
31 drawbacks.

32 The use of agent-based mobility simulations that consider the whole mobility system as
33 finely modelled entities allows us to precisely measure the impact of incentives across various
34 dimensions and on different levels. Generally, the KPIs considered here and the levels at which
35 they are presented can be highly adapted according to the vision and objective of an actor or the
36 other. For instance, if the incentives are financed by municipalities, the impact assessment can be
37 performed distinctively across areas for a better vision on the effect of incentives.

38 An interesting measure is the distribution of daily person walked distances. It is shown in
39 this work that the incentives allow to push this distribution from the lower values, greatly reducing
40 the number of people that do not walk at all or only a short distance throughout the day. The anal-
41 yses of the impact on walked distances can be pushed further to estimate the savings made in the
42 health sector (e.g. social security) thanks to an increased health condition over the population. This
43 can then be included in the estimation of the economic impact of incentives alongside the value of
44 saved GHG emissions. Moreover, the socio-economic impact can be evaluated more exhaustively
45 by employing specific methods. A cost benefit analysis methodology previously proposed for on-

1 demand autonomous vehicles that rely on simulation results can be extended and adapted to the
2 context of monetary incentives(25).

3 **CONCLUSION**

4 To our knowledge, our work is the first quantitative investigation examining monetary incentive
5 policies for walking, under an agent-based modelling and simulation approach. Our approach
6 is illustrated in the context of Île-de-France using open-source tools simulation tools fed with
7 a synthetic population that is built from open data. Moreover, the incentives studies here are
8 presented in details, including how they are integrated in the DMC model. This research and the
9 presented results are consequently fully reproducible and extensible.

10 Various incentive scenarios were investigated, with variations on three dimensions: the
11 amount per kilometer, the types of walks that are targeted and the financing schemes. An extensive
12 study has then been performed by performing simulations with all possible variations of the values
13 considered in each dimension. The impacts of the incentives have been assessed on mobility-
14 centered aspects (mode shares and walked distances), environmental aspects (GHG emissions)
15 and on the economic aspects (cost of the incentives).

16 The results show the potential of approaches relying on agent-based simulations and dis-
17 crete mode choice models for the investigation of monetary incentives. The mode choice model
18 allows the travellers to react to the incentives and the simulation allows to reflect the impact of the
19 incentives and the implied new travel decisions on other aspects of the mobility, which then feed
20 back to the mode choice model. The situation described at the end of the simulation then represents
21 an equilibrium state.

22 Our research presents a high analysis potential and significant extensibility potential. Many
23 development pathways are identified on various aspects of this research. Further developments
24 ought to improve the underlying mode choice model for investigating monetary incentives for
25 walk (e.g. mitigating the possibility of very long walks). Moreover, the studied incentive policies
26 can be extended to consider strategies that target certain trips more specifically, with incentive
27 amounts that are not necessarily linear to the walked distance. Finally, the results obtained with
28 the "polluter pays" financing scheme encourages the investigation of intermediate schemes where
29 only a part of the cost of the incentives is reflected on car users. These pathways will be explored
30 in future works.

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