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# 1 Environmental and welfare gains via urban 2 transport policy portfolios across 120 cities

3 **Charlotte Liotta**<sup>1,2,3,\*</sup>, **Vincent Viguié**<sup>1</sup>, and **Felix Creutzig**<sup>2,3</sup>

4 <sup>1</sup>CIREC, Ecole des Ponts, AgroParisTech, EHESS, CIRAD, CNRS, Université Paris-Saclay,  
5 Nogent-sur-Marne, France

6 <sup>2</sup>Mercator Research Institute on Global Commons and Climate Change, Berlin, Germany

7 <sup>3</sup>Technische Universität Berlin, Berlin, Germany

8 \*To whom correspondence should be addressed; E-mail: [liotta@centre-cired.fr](mailto:liotta@centre-cired.fr).

## 9 **ABSTRACT**

City-level policies are increasingly recognized as key components of strategies to reduce transport greenhouse gas emissions. However, at a global scale, their total efficiencies, costs, and practical feasibility remain unclear. Here, we use a spatially-explicit monocentric urban economic model, systematically calibrated on 120 cities worldwide, to analyze the impact of four representative policies aiming at mitigating transportation GHG emissions, also accounting for their economic welfare impacts and health co-benefits. Applying these policies in all cities, we find that total transportation GHG emissions can be reduced by  
10 31% in 15 years, compared with the baseline scenario. However, the consequences of the same policies vary widely between cities, with specific effects depending on the policy considered, income level, population growth rate, spatial organization, and existing public transport supply. Impacts on transport emissions span from high to almost zero, and consequences in terms of welfare can either be positive or negative. Applying welfare-increasing policy portfolios captures most of the emission reductions: overall, they reduce emissions by 22% in 15 years. Our results highlight that there is no one-size-fits-all policy. However, with context-specific strategies, large emission reductions can globally be achieved while improving welfare.

## 11 **Introduction**

12 Urban action could significantly help to close the gap between Nationally Deter-  
13 mined Contributions (NDCs) and the reductions in emissions needed to keep the  
14 world within +1.5°C of warming<sup>1-3</sup>. This is especially true for urban transportation,  
15 which accounts for about 8% of total emissions<sup>4,5</sup>. However, so far, the actual  
16 potential of such local policies to reduce emissions on a global scale remains

17 largely unknown<sup>6</sup>. Correspondingly, NDCs largely neglect city policies, despite  
18 urban transport emissions being a critical factor in mitigating climate change<sup>7</sup>.  
19 These local policies are also crucial for wider sustainability goals. Decarbonizing  
20 urban transport can indeed bring significant benefits on a large array of issues such  
21 as cleaner air, noise, and road accident reduction, or better health due to the shift to  
22 active transportation modes<sup>8</sup>.

23 Global assessments of the environmental impacts of urban transport policies  
24 have been carried out either using descriptive approaches focusing on current situa-  
25 tions and comparing cities, or using aggregated models aiming at simulating the  
26 potential of future policies. Comparing current emissions in 274 cities worldwide  
27 and using threshold regressions, a 2015 study by Creutzig et al. estimated that  
28 adequate urban planning policies could reduce emissions by about 25% in 2050  
29 compared with a business-as-usual scenario<sup>9</sup>. Using a scenario-based approach  
30 and an aggregated model, the Coalition for Urban Transitions 2019 study estimated  
31 a decrease of 21% in urban transport emissions by 2050 compared to a business-as-  
32 usual scenario, via a reduction in travel demand and a shift to electric and more  
33 efficient vehicles<sup>2</sup>. Using six representative urban archetypes, the 2017 report by  
34 C40 and McKinsey estimated a 22% decrease via transit-oriented development,  
35 new infrastructures for mass transit, walking, cycling, next-generation vehicles, and  
36 commercial freight optimization<sup>10</sup>. Global assessments of transport policies, in-  
37 cluding urban and non-urban transport, have also been carried out using integrated  
38 assessment models (IAMs), studying changes in technologies, infrastructures, and  
39 behaviors<sup>11–18</sup>.

40 However, urban scale policies are difficult to take into account in such studies  
41 because of the complexity to capture the spatial heterogeneity, inside and within  
42 cities, of the travel demand and mode choices of households<sup>19–22</sup>. The local  
43 characteristics of cities, especially their urban forms, significantly impact their  
44 transportation emissions, and the potential efficiency of possible policies<sup>9,23</sup>. For  
45 example, a high population density and the coexistence of spatially distinct job  
46 centers when cities are large enough are associated with lower emissions per  
47 capita<sup>24</sup>. A street-level analysis reveals that households' distances to the city  
48 center and subcenters are a key predictor of urban transport GHG emissions<sup>21</sup>.  
49 Hence, possible mitigation strategies for urban transportation depend on precise  
50 city characteristics, which are difficult to consider globally<sup>25</sup>. For instance, in  
51 sprawled cities, promoting electric vehicles may be more efficient than investing in  
52 mass rapid transit, while the contrary holds in dense cities<sup>26,27</sup>. Another difficulty  
53 comes from the fact that there is an interplay between transport policies and the real  
54 estate market. Transport policies impact housing prices, with large consequences on

55 households' welfare and, indirectly, on long-term changes in transport demand<sup>12,28</sup>.

56 At the local scale, such mechanisms can be taken into account using city  
57 models, such as land-use transport interaction (LUTI) models simulating transport  
58 and land planning policies in cities<sup>29</sup>. Examples are numerous, with rich literature  
59 analyzing case studies in various cities<sup>30–33</sup>. However, generalization is difficult  
60 as this field is highly fragmented, with a large diversity of methods, frameworks,  
61 and indicators, and limited reference to previous works, which does not allow  
62 accumulating knowledge or doing comparisons<sup>32,33</sup>. What is missing is a scalable  
63 approach that provides an assessment for a large number of cities while taking  
64 urban idiosyncrasies into account.

65 Here, we use a spatially-explicit land-use transport interaction model to system-  
66 atically assess and compare, on a collection of 120 cities worldwide (see figure 3),  
67 the consequences of four urban transport policies on public finance, transportation  
68 emission reduction, housing affordability, as well as health benefits due to varia-  
69 tions in air pollution, noise, car accidents and exercise through active transportation  
70 modes. The cities cover all continents except Africa, due to data availability, and  
71 count in total 525 million inhabitants, or about 20% of the total population living  
72 in cities larger than 300 000 inhabitants (see supplementary section C for the city  
73 selection process).

74 The model combines a transport mode choice model with a residential location  
75 choice model derived from the monocentric standard urban economics frame-  
76 work<sup>34,35</sup>. It simulates, in each city, the residential and transportation choices of  
77 households as a function of detailed city characteristics, such as the location of  
78 jobs, transportation costs, and the local land-use policies. The model is calibrated  
79 for each city individually, with parameters structurally estimated using databases of  
80 population densities, transport times, and rent levels within each city (see section  
81 - Methods and Supplementary Section A). Thus, our model enables to simulate  
82 city-level prospective scenarios downscaling global techno-economic scenarios<sup>35</sup>.

83 The four policies that we analyze (Table 1, Supplementary Section E) are  
84 simplified representations of four broad types of city-level transport policies: a  
85 local fuel tax targeting car use, investments in “cleaner” transportation modes with  
86 the development of a bus rapid transit network, a restrictive land-use regulations  
87 policy promoting urban density, in particular near public transport, and a "fuel  
88 efficiency" policy that makes the use of low-emission vehicles mandatory. These  
89 policies are simple enough to be applied to a large sample of cities, but remain  
90 representative of existing policies. We simulate their impact in 2035 in terms of  
91 transportation GHG emissions and social welfare and compare it with a Business-  
92 As-Usual scenario in which we assume the continuation of current trends with no

93 additional city-level policy (see supplementary section D).

## 94 **Results**

### 95 **Aggregated impacts of the four policies**

96 Our analysis demonstrates that policies are effective but affect each city differently  
97 (Figure 1). Indeed, emission reductions typically stand between 21% and 32%  
98 (25th and 75th quantile) with a median reduction of 26%. The combined four  
99 policies could lead to a reduction in annual urban transport emissions of 31%  
100 compared to the baseline scenario over the sample by 2035.

101 This emission reduction is slightly higher than existing global assessments in  
102 the literature but of the same order of magnitude. A 2015 review of local scenarios  
103 of low-carbon urban transport strategies estimated potential global emission reduc-  
104 tion by 20–50% in 2050 compared to baseline scenarios<sup>36</sup>. Using machine learning  
105 to meta-analyze thousands of case studies of climate change mitigation in cities, the  
106 2020 article by Sethi et al. estimated a possible decrease of 28% in 2050 through  
107 travel demand management, fuel shift, and intelligent transportation system (and  
108 potentially more, but with no clear quantification, with pan-city expansions of  
109 public transportation systems and more efficient vehicles)<sup>32</sup>. The two aggregated  
110 studies mentioned at the beginning of this paper estimated, in 2050 also, a possible  
111 decrease of 21% and 22% compared to a baseline scenario<sup>10,37</sup>. Our study suggests  
112 that mitigation can happen earlier than modeled in other studies. A key reason  
113 for this difference is that we model spatially explicit policies, thus broadening the  
114 portfolio of options and improving the resolution of effects.

115 The impact of the policies on households' welfare is complex (Figure 2). They  
116 increase households' financial burden due to the public investment required by  
117 the construction of the BRT system, the increased fuel cost for the fuel tax, or  
118 the increased housing prices, in particular for the restrictive land-use regulations.  
119 However, this burden is counterbalanced by health benefits through decreases in air  
120 pollution, car accidents, and noise, together with an increase in active mode uses<sup>38</sup>.  
121 Finally, households' disposable income increases in the Fuel Tax scenario as tax  
122 revenues are redistributed. The fuel tax revenues depend on distances traveled as  
123 well as on the fuel consumption of private cars: therefore, our model accounts for  
124 the fact that fuel tax revenues decrease if vehicles are becoming more fuel-efficient  
125 or if the share of electric vehicles increases. We find that, when expressed in  
126 monetary terms, benefits do not seem to fully compensate for the financial losses,  
127 leading to an average decrease in welfare by 3.3% (figure 1). This decrease occurs  
128 in almost all cities: the median variation in welfare is -3% and only 11 cities in our

129 sample experience a positive (but moderate) welfare increase.

130 Our computation of welfare suffers from some limitations (see Section Methods  
131 - Outputs of the model and Supplementary Section A.5 for details about the welfare  
132 analysis). For instance, we account for congestion through transportation costs  
133 and, in particular, through the opportunity cost of time, as travel time data have  
134 been measured during rush hour (see Supplementary Section B). However, as we  
135 do not explicitly model congestion, our welfare impacts do not account for the  
136 variations in congestion due to the policies. In supplementary section J, we present  
137 a version of the model in which congestion is, although very simply, explicitly  
138 modeled: it shows that, in the main version of the model, our estimates of the  
139 welfare impacts of the BRT, the fuel tax, and the urban growth boundary policy  
140 are conservative, though we likely overestimate the positive welfare impacts of  
141 the fuel efficiency policy because it increases car use, by rebound effect, thereby  
142 causing traffic congestion.

#### 143 **Policies' effectiveness depends on city characteristics**

144 The four policies' impacts on transportation emissions and welfare are heteroge-  
145 neous (Figures 1 and 2). Depending on the city, emissions reduction ranges from  
146 very high to almost zero, and the BRT, the fuel tax, and the fuel efficiency policy  
147 have a positive welfare impact in some cities and a negative one in others.

148 To better understand this heterogeneity, we try to explain policies' impacts  
149 (welfare variations and emissions variation) by individual city characteristics and  
150 by city archetypes, using linear regressions and principal components respectively  
151 (supplementary section F).

152 The BRT increases welfare and largely mitigates emissions in highly populated,  
153 low-income, and rapidly growing cities with few public transport, in line with  
154 Figure 3 displaying a large mitigation potential of the BRT in South America and a  
155 positive welfare impact in South America and Europe. This finding is consistent  
156 with the fact that this policy is largely developed in this world region<sup>39</sup>. By contrast,  
157 we find that the BRT has a low impact on emissions and a low or negative impact  
158 on welfare in small and high-income cities.

159 Public transportation availability strongly determines the emissions and welfare  
160 impacts of the fuel tax. Indeed, it allows commuters to change transport mode in  
161 response to the tax, which largely mitigates emissions while avoiding them to pay  
162 the full cost of the tax. This result is consistent with the previous findings that  
163 the price elasticity of GHG emissions is twice as high in the short run if public  
164 transport options exist<sup>40</sup>. Accounting for other city characteristics, the fuel tax  
165 has the largest impact on emissions mitigation and the largest positive impact

166 on welfare in large and dense cities, while it has a smaller impact on emissions  
167 and a negative welfare impact in big and sprawled or small cities with few public  
168 transport. Geographically, the fuel tax has the largest emissions mitigation potential  
169 in Europe and South America (Figure 3), where cities are generally dense and/or  
170 have a developed public transport network. Income also matters, with poor cities  
171 being potentially more harmed. Yet, one limitation of our study is that we do  
172 not explicitly model income inequalities, and thus we cannot determine whether  
173 the fuel tax is regressive or progressive. Existing studies find that carbon pricing  
174 might be progressive in the transportation sector in low-income countries as poor  
175 households are less likely to have a car and thus to be affected<sup>41</sup>. Geographically,  
176 the fuel tax has a positive welfare impact in North America, Oceania, and most of  
177 Europe but can be harmful in South America, Eastern Europe, and Asia (Figure 3).

178 The restrictive land-use regulations policy largely mitigates emissions in com-  
179 pact cities with a high modal shift potential (table S8 in supplementary section  
180 F) or in large, poor, and growing cities (table S10 in supplementary section F).  
181 Consistently, Figure 3 shows that the restrictive land-use regulations policy largely  
182 mitigates emissions in South America, parts of China, and parts of Europe. How-  
183 ever, the restrictive land-use regulations policy also has a large negative welfare  
184 impact in growing cities, but that can be mitigated by the availability of public  
185 transport (table S7 in supplementary section F).

186 The fuel efficiency policy is more efficient at mitigating emissions and increas-  
187 ing welfare in small, high-income, or big, poor, and sprawled cities with little  
188 public transportation. It is less beneficial in compact cities, with much public  
189 transportation and low private vehicles modal shares. Consistently, Figure 3 shows  
190 that the fuel efficiency policy has a similar impact in most cities, except in Europe  
191 where emissions mitigation and welfare impacts are lower.

192 However, the characteristics we listed are insufficient to fully explain poli-  
193 cies' impacts, as almost 50% of the variations remain unexplained (the R2s of  
194 the regressions are between 0.24 and 0.54, see supplementary tables S7 and S8 in  
195 supplementary section F). Moreover, for a given policy, the characteristics signifi-  
196 cantly determining its impact on emissions mitigation are generally not the same as  
197 those influencing its welfare impacts. These results highlight the utility of a spatial  
198 model explicitly accounting for cities' spatial characteristics and their interplay to  
199 capture mitigation policies' impacts.

## 200 **Tailored welfare-increasing policy portfolios**

201 As policies' impacts are heterogeneous between cities, alternate policy portfolios  
202 designed in a context-adequate way may have higher efficiencies and fewer negative

203 side-effects than a policy portfolio made of the same policies for all cities. Here,  
204 we simulate a scenario in which we implement, in each city, the policy mix  
205 that maximizes emissions mitigation with the constraints that it has to increase  
206 welfare. This way, we account for the fact that some policies can decrease welfare  
207 when implemented alone, while increasing it when combined with other policies.  
208 In particular, the restrictive land-use regulations policy alone always reduces  
209 inhabitants' welfare, but may increase it when combined with other policies (see  
210 supplementary table S13).

211 In such a scenario, the minimum decrease in urban transport emissions is 15.2%  
212 (the median is 18.0%, and the interquartile range is 16.5% to 23.2%) (Figure 1).  
213 Globally, urban transport emissions are reduced by 22.3%, and welfare increases  
214 on average by 1.0%.

215 Therefore, by designing policies adapted to each city's characteristics, it appears  
216 possible to systematically improve welfare while reducing emissions by more than  
217 two-thirds of the initial figure. These results are a priori underestimated, as the  
218 policy portfolio simulated in this paper is not optimal. The magnitude of emissions  
219 reduction could potentially be increased while keeping welfare variation positive  
220 by tailoring, in greater details, the policies to each city's characteristics, using, for  
221 instance, different tax levels, or designing tailored restrictive land-use regulations  
222 policies.

## 223 **Discussion**

224 The main message of this study is that the current increase in available urban  
225 data allows to model, although simply, the consequences of local policies in a  
226 large set of cities, explicitly accounting for their spatial characteristics. This  
227 enables to downscale global scenarios such as those produced by IAMs at the city  
228 scale and to quantitatively assess the consequences of local strategies involving  
229 land use planning or local transport infrastructure provision under such scenarios.  
230 Moreover, such spatially-explicit modeling also enables to capture the impact of  
231 these strategies on households' expenses related to housing and transport and on  
232 several side-effects of the policies, especially health co-benefits.

233 In line with existing studies, we find that urban forms and cities' spatial charac-  
234 teristics impact the mitigation policies' efficiency in a complex way, with no direct  
235 one-to-one mapping.<sup>9,23,42</sup> Even within the same continent or country, differences  
236 can be large, and city models can help to capture this heterogeneity. In line with  
237 the literature, we also find that the positive side-effects of urban transport policies  
238 can be high, especially regarding the financial cost of these policies.<sup>38</sup> It appears



239 possible to reduce emissions in a welfare-increasing way in each city while keep-  
240 ing most of the global emission reductions. However, a context-adequate policy  
241 portfolio is required with strategies tailored to each city.

242 There are many limitations to the present study. If more and more city-level  
243 data become available, data availability still heavily constrains our modeling and  
244 scenarios. We could not include in our analysis any African city, and there is a  
245 strong geographical bias in favor of developed countries, a common weakness of  
246 the literature on cities.<sup>30</sup> The current increase in available spatialized urban data,  
247 either from direct sources or predicted using machine learning approaches, should  
248 allow expanding our analyses to larger and more representative city samples in  
249 the near future<sup>43,44</sup>. Furthermore, our model is simple and did not consider, for  
250 instance, any mechanism relative to endogenous job locations or description of  
251 income inequalities inside cities. Recently, models capturing these dimensions  
252 have been proposed in the literature and could be used to reproduce our analysis in  
253 the future, when adequate data about the location of jobs and income groups within  
254 cities becomes available.<sup>45</sup> We also ignored cities characterized by high levels of  
255 informal settlements. Indeed, modeling such cities is still a research challenge, as is  
256 the identification of low-carbon and sustainable mobility policies in this context.<sup>46</sup>

257 Using more sophisticated models and additional data may enable to analyze  
258 important policies that we could not assess with our framework. The promotion of  
259 mixed land use, for instance, or the development of bicycle lane networks could not  
260 be evaluated here. We also could not capture the inequalities created by the policies,  
261 something which would require data about where richer and poorer inhabitants live  
262 within each city. The welfare variations and health co-benefits that we simulate  
263 therefore give an indication of the average effect of the policies, but should not be  
264 considered as a direct indication of the political feasibility of their implementation.  
265 With the current and continuous increase in available socio-economic, land-use,  
266 and transport data on cities, however, progresses on these issues may occur in the  
267 coming years.

## 268 **Methods**

### 269 **Urban modeling**

270 For each city individually, we run a spatially-explicit urban model based on the  
271 model NEDUM<sup>28,35</sup>. This model combines a simple transport allocation model  
272 with a land-use model based on the monocentric Standard Urban Model (SUM) of  
273 urban economics, or Alonso-Muth-Mills model<sup>47-49</sup>, with inertia in city evolution.  
274 It allows spatially-explicit modeling of residential and transportation choices of

275 households as a function of employment center locations, transportation costs, and  
276 land-use constraints, which enable the analysis of housing, transport, or land-use  
277 policies.

278 The monocentric SUM is an old model but remains empirically relevant. It has  
279 been shown to capture well the spatial patterns of population density and housing  
280 prices in several cities across the world<sup>34</sup>. For instance, in Berlin, employment  
281 accessibility is a determinant of urban land prices, and the evolution of public  
282 transport supply explains the urban sprawl<sup>50,51</sup>. The recent rise of available ur-  
283 ban data has allowed testing some predictions of the SUM on large numbers of  
284 cities, for instance on urban sprawl in 329 US cities<sup>52</sup>, on urban sprawl and urban  
285 fragmentation in 282 European cities<sup>53</sup>, and on population density and land use  
286 in 300 European cities<sup>54</sup>. The paper written by Liotta et al. (2022) and based on  
287 the same sample of cities than the present paper, in particular, has shown that the  
288 monocentric SUM is capable of capturing the inner structure of these cities, both in  
289 developed and developing countries<sup>55</sup>. In addition, the monocentric SUM requires  
290 a limited amount of data, so that it can be applied to a large number of cities and  
291 suits our approach, and relies on a limited number of hypotheses and mechanisms  
292 so that its outputs are easily interpretable. It is also grounded in microeconomic  
293 theory, offering a robust framework for analysis between location and transport,  
294 contrary to the gravity/spatial interaction approach for instance<sup>56</sup>. Models based on  
295 the SUM have often been used to analyze mitigation and transport policies: to cite  
296 a few recent examples, the construction of the Bus Rapid Transit (BRT) system in  
297 Bogotá<sup>57</sup>, London's Congestion Charge<sup>58</sup>, or an urban growth boundary in Cape  
298 Town<sup>59</sup>.

299 One concern may be that, as cities are growing, they might become less  
300 monocentric, threatening the validity of the monocentric SUM. For instance, while  
301 the monocentric city model adequately represents land values in Chicago at the  
302 beginning of the 20th century, it is not the case anymore at the end of the 20th  
303 century: because of the development of a new airport which became an important  
304 employment center, the city can no longer be considered as monocentric<sup>60</sup>. Still,  
305 recent research papers investigating large samples of cities show that in the vast  
306 majority of them the city center continues to play a predominant role, in the US<sup>61</sup> or  
307 Europe<sup>54</sup>. For instance, in Berlin, even though transportation costs have decreased  
308 and the city has sprawled, the city remains roughly monocentric<sup>62</sup> and distance  
309 to the main center remains the strongest predictor of transportation patterns<sup>21</sup>. In  
310 this paper, we carefully selected our sample of cities to ensure the validity of the  
311 monocentricity assumption (see Supplementary section C). This requirement was  
312 however a limiting factor in the number of cities that we could analyze, and, in the

313 future, the availability of global detailed data on job locations inside cities may  
314 enable to overcome this limit.

315 Our model is fully described in supplementary section A and summarized  
316 below. In a first step, we assume that, within a city, households trade-off between  
317 transportation costs to employment centers and rents per unit of dwelling, resulting  
318 in rents decreasing when transportation costs increase. In this paper, we assume  
319 that households select the transport mode with the lowest generalized transportation  
320 costs, choosing between private cars, public transport, and walking.

321 In a second step, private developers build the amount of housing that maxi-  
322 mizes their profit, accounting for households' bid-rents and for land-use constraints.  
323 Under standard hypotheses on the construction function, this results in the construc-  
324 tion of capital-intensive buildings near employment centers, where bid-rents per  
325 unit of housing are higher. Here, we use a dynamic version of the model, assuming  
326 housing depreciation and inertia in housing construction.

327 As a result, our urban model allows us to estimate population density, housing  
328 supply, transportation choices, and rents as a function of employment centers'  
329 location, transportation infrastructures, and land-use constraints.

### 330 **Outputs of the model**

331 Our model allows to estimate two main outputs at the city level: GHG transportation  
332 emissions and inhabitants' welfare. The computation of these outputs is detailed in  
333 supplementary section A.5 and described below.

334 Transportation emissions are derived from the transportation demand of each  
335 mode and the greenhouse gases intensity of each transportation mode, assuming  
336 that the level of emissions per unit of distance of public transport is fixed and  
337 exogenous and that the level of emissions of private cars per unit of distance  
338 depends on their fuel consumption. Furthermore, we assume that the private  
339 vehicles fleet is homogeneous in fuel consumption in the base year; then, the fuel  
340 consumption of new cars decreases each year at a rate that depends on the scenario,  
341 and we assume a lifespan of private cars of 15 years<sup>63</sup>.

342 Total social welfare is measured as the sum of individual utilities, derived in our  
343 framework from the consumption of housing and composite good, and from health  
344 co-benefits related to transportation. Consumptions of housing and composite good  
345 are constrained by the level of income net of the generalized transportation costs,  
346 meaning that an increase in transportation costs or travel times will, in turn, reduce  
347 welfare. While the consumptions of housing and composite good are standard  
348 outputs of urban economics models, directly resulting from households' utility  
349 maximization, we also include four health co-benefits in our analysis: exposure to

350 noise, air pollution, and car accidents, which negatively impact welfare, and the  
351 positive health impact of active transportation modes.

352 We compute the monetary equivalent of the impacts of air pollution, noise and  
353 car accidents, assuming that they linearly depend on the demand of transportation  
354 from private cars, as well as on the fuel consumption of private cars for air pollution.  
355 For health improvements through active transportation modes, we adapt the HEAT  
356 model of the WHO<sup>64</sup>, assuming that walking or cycling to work brings reduced  
357 mortality, which translates into a monetary gain through the Value of Statistical  
358 Life (VSL). In the HEAT model of the WHO, Values of Statistical Life varies  
359 by country and are based on a comprehensive review published by the OECD<sup>65</sup>.  
360 We include these co-benefits in the utility function as described in supplementary  
361 section A.2.

#### 362 **Data sources and parameters calibration**

363 We individually calibrate the model's city-specific parameters on each city of the  
364 sample using spatially-explicit data on population densities, rents, transportation  
365 costs, land use, and dwelling sizes for the 120 cities for 2015 (see supplementary  
366 section A.6). Due to data availability, our model is monocentric: in each city, we  
367 only consider the city center as the main employment center. We carefully selected  
368 our sample of cities to ensure the validity of the monocentricity assumption (see  
369 supplementary section C for a description of the sample selection process as well  
370 Methods - Urban modeling section and Supplementary section A.1 for a more  
371 detailed discussion of the monocentricity assumption).

372 We use the dataset from Lepetit et al. (2022)<sup>66</sup>, which provides spatially explicit  
373 data on population densities, rents, dwelling sizes, land use, and transportation  
374 costs for 191 cities on five continents at a 1km-resolution. Population density and  
375 land cover are from the GHS-POP<sup>67</sup> and the ESA CCI<sup>68</sup> databases respectively,  
376 while transportation and real estate data have been obtained from the Google Maps  
377 API and the web scraping of real estate websites. This dataset is the first including  
378 spatialized data on real estate and transportation in a large sample of cities covering  
379 both developed and developing countries and allowing an integrated analysis of  
380 density, real estate, transportation, and land use. In addition, we use city-level data  
381 on city characteristics, including incomes, the fuel consumption of private vehicles,  
382 fuel costs, and agricultural rents. In particular, the fuel consumption of private  
383 vehicles in the base year is given by the IEA report *Fuel Economy in Major Car*  
384 *Markets*<sup>69</sup>. All data sources are in supplementary section B.

385 We tried to assess the model's ability to reproduce urban structures: results can  
386 be found in Supplementary Section A.7 and are summarized below. First, within

387 each city, we compared simulated densities and rents with density and real estate  
388 data (Figure S2, Table S1, Figure S3). For densities, the fit between the model  
389 and the data is generally good, with a minimum correlation coefficient of 0.31, a  
390 median of 0.63, and a maximum of 0.89. For rents, the fit is good for most cities  
391 (median of the correlation coefficients of 0.46, maximum of 0.84) but is low for  
392 others (the correlation coefficient is below 0.32 for 25% of the cities). The fit  
393 between the model and density data is the best for Europe and South America and  
394 the lowest for North America, with heterogeneity within continents as well. Liotta  
395 et al. (2022)<sup>55</sup> highlight city characteristics that might explain the poor fit of the  
396 Standard Urban Model in some cities and world regions, including polycentricity,  
397 informal housing, and local amenities.

398 Then, at the city level, we compared simulated modal shares and transportation  
399 emission levels with existing data. For modal shares, we compared the model's  
400 outputs with three existing databases: Deloitte data<sup>70</sup>, CDP data (<https://data.cdp.net>), and EPOMM data (<https://epomm.eu>) (table S2). Among the 76  
402 cities that are in common between our sample and at least one of these three  
403 databases, the Pearson coefficient of correlation is 0.36 (p-value < 0.01) for private  
404 cars, 0.63 (p-value < 0.01) for public transport, and 0.05 for active modes. An  
405 explanation for the poor fit on active modes is that, as external databases often  
406 have narrower definitions of urban boundaries, usually limited to administrative  
407 boundaries, they tend to overestimate the modal share of walking and cycling  
408 compared to our model. Another explanation is that the external databases come  
409 from the aggregation of many sources (self-reported data by cities, governments,  
410 NGOs, expert judgments, etc.), threatening the validity of the comparisons between  
411 cities.

412 Regarding transportation emissions, we compared the model's outputs with  
413 external databases (table S3): Moran et al. (2018)<sup>71</sup>, Nangini et al. (2019)<sup>72</sup>, and  
414 Kona et al. (2021)<sup>73</sup>. We find a Pearson correlation coefficient of 0.45 (p-value <  
415 0.05) with Nangini et al., 0.32 (p-value < 0.1) with Kona et al., and 0.53 (p-value  
416 < 0.01) with Moran et al. However, two elements question the relevance of the  
417 comparison. First, Moran et al. and Nangini et al. only report total emissions,  
418 whereas our estimates are for transport emissions. Second, the external data  
419 themselves are not consistent: comparing the databases on the cities they have  
420 in common, we find a correlation coefficient of 0.41 (p-value of 0.000) between  
421 Nangini et al.'s and Moran et al.'s data, a correlation coefficient of 0.16 (p-value of  
422 0.573) between Nangini et al.'s and Kona et al.'s data, and a correlation coefficient  
423 of 0.04 (p-value of 0.843) between Moran et al.'s and Kona et al.'s data. Indeed,  
424 the methodologies of the three databases differ: Nangini et al. and Kona et al. use

425 a bottom-up approach, with cities reporting their emissions, whereas Moran et al.  
426 use a top-down approach, downscaling national or subnational emissions at the city  
427 scale; Nangini et al. report Scope 1 emissions, Kona et al. report direct transport  
428 emissions and Moran et al. Scope 3 emissions.

## 429 **Scenarios**

430 The baseline scenario is a business-as-usual (BAU) scenario, assuming the continu-  
431 ation of current trends with no additional city-level mitigation policies. It uses the  
432 income per capita growth scenarios from the global integrated assessment model  
433 (IAM) IMACLIM-R<sup>74</sup>. In particular, it uses the baseline scenario based on the  
434 "middle of the road" SSP2, which is quite standard in the IAM community and  
435 corresponds to a central scenario.

436 For population, it uses the population growth scenarios of the *World Urbaniza-*  
437 *tion Prospects* of the United Nations<sup>75</sup>, which provide population growth projec-  
438 tions from 2015 to 2035. Compared to the SSPs, the United Nations projections  
439 have the advantage of being available at the city level for cities of more than 300  
440 000 inhabitants. In addition, population growth projections of the United Nations  
441 are broadly consistent with SSP2 at the global level in terms of population size for  
442 the first half of the 21st century<sup>76</sup>. Still, the SSP2 relies on underlying hypotheses  
443 in terms of age, sex, and education that lead to differences in fertility rates, and in  
444 turn, in population growth scenarios compared with the United Nations scenarios:  
445 for instance, the SSP2 assumes lower fertility rates for Africa than the United  
446 Nations, leading to population size differences in the long run.

447 Finally, we assume that there is no change in public transports infrastructures  
448 and that the fuel consumption of new private cars decreases by 1.0% per year, in  
449 line with current trends for light-duty vehicles<sup>77</sup>, assuming a vehicle lifespan of 15  
450 years<sup>63</sup>. More details about our BAU scenario are in supplementary section D.

451 We also run our four policy scenarios, designed to be representative of a wide  
452 spectrum of potential urban policies, yet simple enough to be generically applied  
453 to our sample of cities. We assume the same trends for population and income as in  
454 the BAU scenario, while transportation infrastructures and land-use constraints are  
455 impacted by the policies. Details about the policy scenarios are in supplementary  
456 section E.

## 457 **Robustness checks**

458 In supplementary section I, we carry out a robustness check of the results of this  
459 paper: we simulate an alternative version of each type of policy and check that the  
460 results remain qualitatively the same.

461 More precisely, we assume, starting in 2020, that the fuel tax increases fuel  
462 prices by 10% instead of 30%, that the fuel efficiency policy reduces the fuel  
463 consumption of new vehicles by 2% each year instead of 3.7%, and that the  
464 restrictive land-use regulations policy prevents new constructions in areas with  
465 a density below 400 inhabitants per km<sup>2</sup> in 2020, unless inhabitants will use  
466 public transport or active modes. For the BRT, instead of using OpenStreetMap  
467 street network data, we assume more simply that two new public transport lines,  
468 North-South and East-West, are opened in each city.

469 Results are qualitatively the same as with the main policies' specifications.  
470 The combined four policies allow mitigating transport emissions by 12.1% in 15  
471 years, with large heterogeneity in policies' efficiencies between cities. However,  
472 city-specific policy portfolios that maximize emissions mitigation while increasing  
473 welfare allow keeping most of the emissions mitigation (-11.6%) while increasing  
474 average welfare by 0.9%.

## 475 **Data availability**

476 This study is largely based on the following data paper:

477 Lepetit, Q., Viguié, V., Liotta, C. A gridded dataset on densities, real estate prices,  
478 transport, and land use inside 192 worldwide urban areas. *Data in Brief* 47, 108962  
479 (2023). <https://doi.org/10.1016/j.dib.2023.108962>

480 Data from this data paper are available here: [https://zenodo.org/record/  
481 7086267](https://zenodo.org/record/7086267).

482 Complementary data have been used as inputs for the model:

483 • World bank data on gasoline prices ([https://data.worldbank.org/indicator/  
484 EP.PMP.SGAS.CD](https://data.worldbank.org/indicator/EP.PMP.SGAS.CD), accessed in April 2023)

485 • Data on average car fuel consumption per country from the International  
486 Energy Agency 2019 report *Fuel Economy in Major Car Markets* ([https://  
487 www.iea.org/reports/fuel-economy-in-major-car-markets](https://www.iea.org/reports/fuel-economy-in-major-car-markets), accessed  
488 in April 2023).

489 • Data on the monetary cost of public transport from:

490 – Numbeo ([https://www.numbeo.com/cost-of-living/country\\_  
491 price\\_rankings?itemId=18](https://www.numbeo.com/cost-of-living/country_price_rankings?itemId=18), accessed in April 2023)

492 – kiwi.fr ([https://www.kiwi.com/stories/cheapest-and-most-expensive-public-tr  
493 accessed in April 2023](https://www.kiwi.com/stories/cheapest-and-most-expensive-public-tr))

494 – Wordatlas (<https://www.worldatlas.com/articles/cost-of-public-transportation.html>,  
495 [html](https://www.worldatlas.com/articles/cost-of-public-transportation.html), accessed in April 2023).

496 • Data on income:

497 – OECD GDP per capita at the city scale data (<https://stats.oecd.org/Index.aspx?DataSetCode=CITIES>,  
498 [accessed in April 2023](https://stats.oecd.org/Index.aspx?DataSetCode=CITIES))

499 – Brookings GDP per capita at the city scale data (*Redefining Global*  
500 *Cities* 2016 report from the Brookings Institution, <https://www.brookings.edu/research/redefining-global-cities/>)  
501

502 – World Bank GDP per capita at the country scale data (<https://data.worldbank.org/indicator/NY.GDP.PCAP.PP.CD>,  
503 [accessed in April 2023](https://data.worldbank.org/indicator/NY.GDP.PCAP.PP.CD)).

504

505 • Agricultural GDP and agricultural areas by country data from the FAO  
506 (<https://www.fao.org/faostat/en/#home>, accessed in April 2023).

507 • Population growth scenarios from the *World Urbanization Prospects – the*  
508 *2018 Revisions* of the United Nations (<https://population.un.org/wup/Download/>,  
509 [accessed in April 2023](https://population.un.org/wup/Download/)).

510 • Marginal costs of air pollution, noise and car accidents from the report  
511 *External costs of transport in Europe*, van Essen et al., 2019. <https://trid.trb.org/view/1646234>,  
512 [accessed in April 2019](https://trid.trb.org/view/1646234).

513 Complementary datasets have been used for calibrations' validation:

514 • Modal shares data from the following datasets:

515 – EPOMM (<https://epomm.eu>, accessed in April 2023)

516 – CDP (<https://data.cdp.net>, accessed in April 2023)

517 – Deloitte (report *The 2019 Deloitte City Mobility Index*, Dixon et al.,  
518 2019. <https://www2.deloitte.com/content/dam/Deloitte/br/Documents/consumer-business/City-Mobility-Index-2019.pdf>,  
519 [accessed in April 2023](https://www2.deloitte.com/content/dam/Deloitte/br/Documents/consumer-business/City-Mobility-Index-2019.pdf))  
520

521 • Emissions datasets from the following papers:



- 522 – Moran, D. et al. Carbon footprints of 13 000 cities. *Environ. Res. Lett.*  
523 13, 064041 (2018). DOI 10.1088/1748-9326/aac72a.
- 524 – Nangini, C. et al. A global dataset of CO<sub>2</sub> emissions and ancillary  
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526 (2019). <https://doi.org/10.1038/sdata.2018.280>
- 527 – Kona, A. et al. Global Covenant of Mayors, a dataset of GHG emis-  
528 sions for 6,200 cities in Europe and the Southern Mediterranean. *Earth*  
529 *System Science Data Discussions* 1–17 (2021) doi:10.5194/essd-2021-  
530 67.

### 531 **Code availability**

532 The analyses have been done using Python 3.9. Codes are available: [https:](https://github.com/CIRED/policy_portfolios)  
533 [//github.com/CIRED/policy\\_portfolios](https://github.com/CIRED/policy_portfolios).

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### 543 **Author Contributions**

544 The study was conceived by C.L., V.V., and F.C. Analysis was performed by C.L.,  
545 in consultation and with inputs from V.V and F.C. All authors discussed the results  
546 and contributed to the writing of the paper.

### 547 **Competing Interests**

548 The authors declare no competing interests.

### 549 **Tables**

Policy name	Description
BAU	Continuation of current trends. We assume that, in each city, there is a fleet of private cars homogeneous in fuel consumption in the base year. In the BAU scenario, the fuel consumption of new cars decreases by 1% per year <sup>77</sup> , and the lifespan of private cars is 15 years <sup>63</sup> . Income per capita growth scenarios are taken from the global Integrated Assessment Model IMACLIM-R <sup>74</sup> and population growth scenarios from the World Urbanization Prospects of the United Nations <sup>75</sup> (see section Methods - Scenarios and supplementary section D).
Fuel tax	Same assumptions as in the BAU scenario, except that fuel price increases by 30% compared to the business-as-usual scenario (broadly corresponding to a level of carbon pricing of US \$50–100/tCO <sub>2</sub> , the level required to cost-effectively reduce emissions in line with the temperature goals of the Paris Agreement <sup>78</sup> ). This fuel tax, therefore, affects all private cars, proportionally to the average fuel consumption of the fleet (the implications of this simplifying assumption are discussed in supplementary section E). Local tax revenues are redistributed uniformly among inhabitants.
Bus Rapid Transit (BRT)	Same assumptions as in the BAU scenario, except for the construction of a Bus Rapid Transit (BRT) network on all main streets of the city (identified using OpenStreetMap). The new BRT has a uniform speed of 40km/h and a construction cost of 12.23 million USD per km, equally shared by households over 50 years with a 5% interest rate.
Restrictive land-use regulations	Same assumptions as in the BAU scenario, except that new construction beyond places already built in 2020 is forbidden unless inhabitants have access to mass public transport. To accommodate the growing population, cities have to become denser. The associated increase in housing prices can negatively impact inhabitants' welfare. <sup>28</sup>
Fuel efficiency	Same assumptions that in the BAU scenario, except that the fuel consumption of new cars decreases by 3.7% per year instead of 1%, in line with the IEA "2°C Scenario" <sup>77</sup> .

**Table 1.** Policies analyzed (see Supplementary Section E for a detailed description).

## 550 **Figure Captions**

551 **Figure 1.** Impact of the four policies on annual transport emissions and average  
552 welfare in the 120 cities in 2035, compared with the business-as-usual scenario.  
553 *Each dot represents a city. The boxplots represent the first quartile, the median  
554 and the third quartile among cities, and the whiskers correspond to 1.5 times the  
555 interquartile range. The numbers above the box plots represent the aggregated  
556 mean of changes, accounting for cities' population sizes.*

557 **Figure 2.** Decomposition of welfare variations between different drivers in the  
558 120 cities.

559 *The figures represent the variation in 2035 compared to the business-as-usual  
560 scenario. The boxplots represent the first quartile, the median and the third  
561 quartile among cities, and the whiskers correspond to 1.5 times interquartile range.  
562 Disposable income is the variation of income due to local taxes (fuel tax revenues  
563 are redistributed uniformly among the inhabitants of each city, hence increasing  
564 disposable income, while the construction of the BRT is financed by households,  
565 hence decreasing their income).*

566 **Figure 3.** Effect of the four policies on urban transport emissions and on welfare  
567 (including direct and indirect financial cost of the policies and health co-benefits)  
568 in 2035, compared to the business-as-usual scenario.

569 *See also supplementary figures S11 and S12.*

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