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

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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 welfareincreasing 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.

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
- world within $+1.5^{\circ}$ C of warming¹⁻³. This is especially true for urban transportation,
- ¹⁵ which accounts for about 8% of total emissions^{4,5}. However, so far, the actual
- ¹⁶ potential of such local policies to reduce emissions on a global scale remains

largely unknown⁶. Correspondingly, NDCs largely neglect city policies, despite
urban transport emissions being a critical factor in mitigating climate change⁷.
These local policies are also crucial for wider sustainability goals. Decarbonizing
urban transport can indeed bring significant benefits on a large array of issues such
as cleaner air, noise, and road accident reduction, or better health due to the shift to
active transportation modes⁸.

Global assessments of the environmental impacts of urban transport policies 23 have been carried out either using descriptive approaches focusing on current situa-24 tions and comparing cities, or using aggregated models aiming at simulating the 25 potential of future policies. Comparing current emissions in 274 cities worldwide 26 and using threshold regressions, a 2015 study by Creutzig et al. estimated that 27 adequate urban planning policies could reduce emissions by about 25% in 2050 28 compared with a business-as-usual scenario⁹. Using a scenario-based approach 29 and an aggregated model, the Coalition for Urban Transitions 2019 study estimated 30 a decrease of 21% in urban transport emissions by 2050 compared to a business-as-3. usual scenario, via a reduction in travel demand and a shift to electric and more 32 efficient vehicles². Using six representative urban archetypes, the 2017 report by 33 C40 and McKinsey estimated a 22% decrease via transit-oriented development, 34 new infrastructures for mass transit, walking, cycling, next-generation vehicles, and 35 commercial freight optimization¹⁰. Global assessments of transport policies, in-36 cluding urban and non-urban transport, have also been carried out using integrated 37 assessment models (IAMs), studying changes in technologies, infrastructures, and 38 behaviors^{11–18}. 39

However, urban scale policies are difficult to take into account in such studies 40 because of the complexity to capture the spatial heterogeneity, inside and within 41 cities, of the travel demand and mode choices of households^{19–22}. The local 42 characteristics of cities, especially their urban forms, significantly impact their 43 transportation emissions, and the potential efficiency of possible policies 9,23 . For 44 example, a high population density and the coexistence of spatially distinct job 45 centers when cities are large enough are associated with lower emissions per 46 capita²⁴. A street-level analysis reveals that households' distances to the city 47 center and subcenters are a key predictor of urban transport GHG emissions²¹. 48 Hence, possible mitigation strategies for urban transportation depend on precise 49 city characteristics, which are difficult to consider globally²⁵. For instance, in 50 sprawled cities, promoting electric vehicles may be more efficient than investing in 51 mass rapid transit, while the contrary holds in dense cities 26,27 . Another difficulty 52 comes from the fact that there is an interplay between transport policies and the real 53 estate market. Transport policies impact housing prices, with large consequences on 54

households' welfare and, indirectly, on long-term changes in transport demand^{12,28}. 55 At the local scale, such mechanisms can be taken into account using city 56 models, such as land-use transport interaction (LUTI) models simulating transport 57 and land planning policies in cities²⁹. Examples are numerous, with rich literature 58 analyzing case studies in various cities 30-33. However, generalization is difficult 59 as this field is highly fragmented, with a large diversity of methods, frameworks, 60 and indicators, and limited reference to previous works, which does not allow 61 accumulating knowledge or doing comparisons^{32,33}. What is missing is a scalable 62 approach that provides an assessment for a large number of cities while taking 63 urban idiosyncrasies into account. 64

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

The model combines a transport mode choice model with a residential location 74 choice model derived from the monocentric standard urban economics frame-75 work^{34,35}. It simulates, in each city, the residential and transportation choices of 76 households as a function of detailed city characteristics, such as the location of 77 jobs, transportation costs, and the local land-use policies. The model is calibrated 78 for each city individually, with parameters structurally estimated using databases of 79 population densities, transport times, and rent levels within each city (see section 80 - Methods and Supplementary Section A). Thus, our model enables to simulate 81 city-level prospective scenarios downscaling global techno-economic scenarios³⁵. 82 The four policies that we analyze (Table 1, Supplementary Section E) are 83 simplified representations of four broad types of city-level transport policies: a 84 local fuel tax targeting car use, investments in "cleaner" transportation modes with 85 the development of a bus rapid transit network, a restrictive land-use regulations 86 policy promoting urban density, in particular near public transport, and a "fuel 87 efficiency" policy that makes the use of low-emission vehicles mandatory. These 88 policies are simple enough to be applied to a large sample of cities, but remain 89 representative of existing policies. We simulate their impact in 2035 in terms of 90 transportation GHG emissions and social welfare and compare it with a Business-91 As-Usual scenario in which we assume the continuation of current trends with no 92

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

94 Results

Aggregated impacts of the four policies

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

This emission reduction is slightly higher than existing global assessments in 101 the literature but of the same order of magnitude. A 2015 review of local scenarios 102 of low-carbon urban transport strategies estimated potential global emission reduc-103 tion by 20–50% in 2050 compared to baseline scenarios³⁶. Using machine learning 104 to meta-analyze thousands of case studies of climate change mitigation in cities, the 105 2020 article by Sethi et al. estimated a possible decrease of 28% in 2050 through 106 travel demand management, fuel shift, and intelligent transportation system (and 107 potentially more, but with no clear quantification, with pan-city expansions of 108 public transportation systems and more efficient vehicles)³². The two aggregated 109 studies mentioned at the beginning of this paper estimated, in 2050 also, a possible 110 decrease of 21% and 22% compared to a baseline scenario^{10,37}. Our study suggests 111 that mitigation can happen earlier than modeled in other studies. A key reason 112 for this difference is that we model spatially explicit policies, thus broadening the 113 portfolio of options and improving the resolution of effects. 114

The impact of the policies on households' welfare is complex (Figure 2). They 115 increase households' financial burden due to the public investment required by 116 the construction of the BRT system, the increased fuel cost for the fuel tax, or 117 the increased housing prices, in particular for the restrictive land-use regulations. 118 However, this burden is counterbalanced by health benefits through decreases in air 119 pollution, car accidents, and noise, together with an increase in active mode uses³⁸. 120 Finally, households' disposable income increases in the Fuel Tax scenario as tax 121 revenues are redistributed. The fuel tax revenues depend on distances traveled as 122 well as on the fuel consumption of private cars: therefore, our model accounts for 123 the fact that fuel tax revenues decrease if vehicles are becoming more fuel-efficient 124 or if the share of electric vehicles increases. We find that, when expressed in 125 monetary terms, benefits do not seem to fully compensate for the financial losses, 126 leading to an average decrease in welfare by 3.3% (figure 1). This decrease occurs 127 in almost all cities: the median variation in welfare is -3% and only 11 cities in our 128

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

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

¹⁴³ Policies' effectiveness depends on city characteristics

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

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

The BRT increases welfare and largely mitigates emissions in highly populated, low-income, and rapidly growing cities with few public transport, in line with Figure 3 displaying a large mitigation potential of the BRT in South America and a positive welfare impact in South America and Europe. This finding is consistent with the fact that this policy is largely developed in this world region³⁹. By contrast, we find that the BRT has a low impact on emissions and a low or negative impact 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 exist⁴⁰. Accounting for other city characteristics, the fuel tax ¹⁶⁵ has the largest impact on emissions mitigation and the largest positive impact

on welfare in large and dense cities, while it has a smaller impact on emissions 166 and a negative welfare impact in big and sprawled or small cities with few public 167 transport. Geographically, the fuel tax has the largest emissions mitigation potential 168 in Europe and South America (Figure 3), where cities are generally dense and/or 169 have a developed public transport network. Income also matters, with poor cities 170 being potentially more harmed. Yet, one limitation of our study is that we do 171 not explicitly model income inequalities, and thus we cannot determine whether 172 the fuel tax is regressive or progressive. Existing studies find that carbon pricing 173 might be progressive in the transportation sector in low-income countries as poor 174 households are less likely to have a car and thus to be affected⁴¹. Geographically, 175 the fuel tax has a positive welfare impact in North America, Oceania, and most of 176 Europe but can be harmful in South America, Eastern Europe, and Asia (Figure 3). 177 The restrictive land-use regulations policy largely mitigates emissions in com-178 pact cities with a high modal shift potential (table S8 in supplementary section 179 F) or in large, poor, and growing cities (table S10 in supplementary section F). 180 Consistently, Figure 3 shows that the restrictive land-use regulations policy largely 181 mitigates emissions in South America, parts of China, and parts of Europe. How-182 ever, the restrictive land-use regulations policy also has a large negative welfare 183

impact in growing cities, but that can be mitigated by the availability of public
 transport (table S7 in supplementary section F).

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

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

200 Tailored welfare-increasing policy portfolios

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

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

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

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

223 Discussion

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

In line with existing studies, we find that urban forms and cities' spatial characteristics impact the mitigation policies' efficiency in a complex way, with no direct one-to-one mapping.^{9,23,42} Even within the same continent or country, differences can be large, and city models can help to capture this heterogeneity. In line with the literature, we also find that the positive side-effects of urban transport policies can be high, especially regarding the financial cost of these policies.³⁸ It appears possible to reduce emissions in a welfare-increasing way in each city while keep ing most of the global emission reductions. However, a context-adequate policy
 portfolio is required with strategies tailored to each city.

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

Using more sophisticated models and additional data may enable to analyze 257 important policies that we could not assess with our framework. The promotion of 258 mixed land use, for instance, or the development of bicycle lane networks could not 259 be evaluated here. We also could not capture the inequalities created by the policies, 260 something which would require data about where richer and poorer inhabitants live 26 within each city. The welfare variations and health co-benefits that we simulate 262 therefore give an indication of the average effect of the policies, but should not be 263 considered as a direct indication of the political feasibility of their implementation. 264 With the current and continuous increase in available socio-economic, land-use, 265 and transport data on cities, however, progresses on these issues may occur in the 266 coming years. 267

268 Methods

Urban modeling

For each city individually, we run a spatially-explicit urban model based on the model NEDUM^{28, 35}. This model combines a simple transport allocation model with a land-use model based on the monocentric Standard Urban Model (SUM) of urban economics, or Alonso-Muth-Mills model^{47–49}, with inertia in city evolution. It allows spatially-explicit modeling of residential and transportation choices of households as a function of employment center locations, transportation costs, and
land-use constraints, which enable the analysis of housing, transport, or land-use
policies.

The monocentric SUM is an old model but remains empirically relevant. It has 278 been shown to capture well the spatial patterns of population density and housing 279 prices in several cities across the world³⁴. For instance, in Berlin, employment 280 accessibility is a determinant of urban land prices, and the evolution of public 28 transport supply explains the urban sprawl 50,51 . The recent rise of available ur-282 ban data has allowed testing some predictions of the SUM on large numbers of 283 cities, for instance on urban sprawl in 329 US cities⁵², on urban sprawl and urban 284 fragmentation in 282 European cities⁵³, and on population density and land use 285 in 300 European cities⁵⁴. The paper written by Liotta et al. (2022) and based on 286 the same sample of cities than the present paper, in particular, has shown that the 287 monocentric SUM is capable of capturing the inner structure of these cities, both in 288 developed and developing countries⁵⁵. In addition, the monocentric SUM requires 289 a limited amount of data, so that it can be applied to a large number of cities and 290 suits our approach, and relies on a limited number of hypotheses and mechanisms 29 so that its outputs are easily interpretable. It is also grounded in microeconomic 292 theory, offering a robust framework for analysis between location and transport, 293 contrary to the gravity/spatial interaction approach for instance⁵⁶. Models based on 294 the SUM have often been used to analyze mitigation and transport policies: to cite 295 a few recent examples, the construction of the Bus Rapid Transit (BRT) system in 296 Bogotá⁵⁷, London's Congestion Charge⁵⁸, or an urban growth boundary in Cape 297 Town⁵⁹. 298

One concern may be that, as cities are growing, they might become less 290 monocentric, threatening the validity of the monocentric SUM. For instance, while 300 the monocentric city model adequately represents land values in Chicago at the 301 beginning of the 20th century, it is not the case anymore at the end of the 20th 302 century: because of the development of a new airport which became an important 303 employment center, the city can no longer be considered as monocentric⁶⁰. Still, 304 recent research papers investigating large samples of cities show that in the vast 305 majority of them the city center continues to play a predominant role, in the US^{61} or 306 Europe⁵⁴. For instance, in Berlin, even though transportation costs have decreased 307 and the city has sprawled, the city remains roughly monocentric⁶² and distance 308 to the main center remains the strongest predictor of transportation patterns²¹. In 309 this paper, we carefully selected our sample of cities to ensure the validity of the 310 monocentricity assumption (see Supplementary section C). This requirement was 311 however a limiting factor in the number of cities that we could analyze, and, in the 312

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

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

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

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

Outputs of the model

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

Transportation emissions are derived from the transportation demand of each 334 mode and the greenhouse gases intensity of each transportation mode, assuming 335 that the level of emissions per unit of distance of public transport is fixed and 336 exogenous and that the level of emissions of private cars per unit of distance 337 depends on their fuel consumption. Furthermore, we assume that the private 338 vehicles fleet is homogeneous in fuel consumption in the base year; then, the fuel 339 consumption of new cars decreases each year at a rate that depends on the scenario, 340 and we assume a lifespan of private cars of 15 years⁶³. 341

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

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

We compute the monetary equivalent of the impacts of air pollution, noise and 352 car accidents, assuming that they linearly depend on the demand of transportation 353 from private cars, as well as on the fuel consumption of private cars for air pollution. 354 For health improvements through active transportation modes, we adapt the HEAT 355 model of the WHO⁶⁴, assuming that walking or cycling to work brings reduced 356 mortality, which translates into a monetary gain through the Value of Statistical 357 Life (VSL). In the HEAT model of the WHO, Values of Statistical Life varies 358 by country and are based on a comprehensive review published by the OECD⁶⁵. 359 We include these co-benefits in the utility function as described in supplementary 360 section A.2. 361

362 Data sources and parameters calibration

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

We use the dataset from Lepetit et al. $(2022)^{66}$, which provides spatially explicit 372 data on population densities, rents, dwelling sizes, land use, and transportation 373 costs for 191 cities on five continents at a 1km-resolution. Population density and 374 land cover are from the GHS-POP⁶⁷ and the ESA CCI⁶⁸ databases respectively. 375 while transportation and real estate data have been obtained from the Google Maps 376 API and the web scraping of real estate websites. This dataset is the first including 377 spatialized data on real estate and transportation in a large sample of cities covering 378 both developed and developing countries and allowing an integrated analysis of 379 density, real estate, transportation, and land use. In addition, we use city-level data 380 on city characteristics, including incomes, the fuel consumption of private vehicles, 381 fuel costs, and agricultural rents. In particular, the fuel consumption of private 382 vehicles in the base year is given by the IEA report *Fuel Economy in Major Car* 383 *Markets*⁶⁹. All data sources are in supplementary section B. 384

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

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

Then, at the city level, we compared simulated modal shares and transportation 398 emission levels with existing data. For modal shares, we compared the model's 399 outputs with three existing databases: Deloitte data⁷⁰, CDP data (https://data. 400 cdp.net), and EPOMM data (https://epomm.eu) (table S2). Among the 76 401 cities that are in common between our sample and at least one of these three 402 databases, the Pearson coefficient of correlation is 0.36 (p-value < 0.01) for private 403 cars, 0.63 (p-value < 0.01) for public transport, and 0.05 for active modes. An 404 explanation for the poor fit on active modes is that, as external databases often 405 have narrower definitions of urban boundaries, usually limited to administrative 406 boundaries, they tend to overestimate the modal share of walking and cycling 407 compared to our model. Another explanation is that the external databases come 408 from the aggregation of many sources (self-reported data by cities, governments, 409 NGOs, expert judgments, etc.), threatening the validity of the comparisons between 410 cities. 411

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

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

429 Scenarios

The baseline scenario is a business-as-usual (BAU) scenario, assuming the continuation of current trends with no additional city-level mitigation policies. It uses the income per capita growth scenarios from the global integrated assessment model (IAM) IMACLIM-R⁷⁴. In particular, it uses the baseline scenario based on the "middle of the road" SSP2, which is quite standard in the IAM community and corresponds to a central scenario.

For population, it uses the population growth scenarios of the World Urbaniza-436 *tion Prospects* of the United Nations⁷⁵, which provide population growth projec-437 tions from 2015 to 2035. Compared to the SSPs, the United Nations projections 438 have the advantage of being available at the city level for cities of more than 300 439 000 inhabitants. In addition, population growth projections of the United Nations 440 are broadly consistent with SSP2 at the global level in terms of population size for 441 the first half of the 21st century⁷⁶. Still, the SSP2 relies on underlying hypotheses 442 in terms of age, sex, and education that lead to differences in fertility rates, and in 443 turn, in population growth scenarios compared with the United Nations scenarios: 444 for instance, the SSP2 assumes lower fertility rates for Africa than the United 445 Nations, leading to population size differences in the long run. 446

Finally, we assume that there is no change in public transports infrastructures and that the fuel consumption of new private cars decreases by 1.0% per year, in line with current trends for light-duty vehicles⁷⁷, assuming a vehicle lifespan of 15 years⁶³. More details about our BAU scenario are in supplementary section D.

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

457 **Robustness checks**

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

More precisely, we assume, starting in 2020, that the fuel tax increases fuel 461 prices by 10% instead of 30%, that the fuel efficiency policy reduces the fuel 462 consumption of new vehicles by 2% each year instead of 3.7%, and that the 463 restrictive land-use regulations policy prevents new constructions in areas with 464 a density below 400 inhabitants per km2 in 2020, unless inhabitants will use 465 public transport or active modes. For the BRT, instead of using OpenStreetMap 466 street network data, we assume more simply that two new public transport lines, 467 North-South and East-West, are opened in each city. 468

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

475 Data availability

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

83	• World bank data on gasoline prices (https://data.worldbank.org/indicator/
84	EP.PMP.SGAS.CD, accessed in April 2023)
85	• Data on average car fuel consumption per country from the International
86	Energy Agency 2019 report <i>Fuel Economy in Major Car Markets</i> (https://
87	www.iea.org/reports/fuel-economy-in-major-car-markets, accessed
88	in April 2023).
89	• Data on the monetary cost of public transport from:
90	- Numbeo (https://www.numbeo.com/cost-of-living/country_
91	price_rankings?itemId=18, accessed in April 2023)
92	 kiwi.fr(https://www.kiwi.com/stories/cheapest-and-most-expensive-public-tr
93	accessed in April 2023)

494 495	- Wordatlas (https://www.worldatlas.com/articles/cost-of-public-transportation html, accessed in April 2023).	
496	• Data on income:	
497 498	 OECD GDP per capita at the city scale data (https://stats.oecd. org/Index.aspx?DataSetCode=CITIES, accessed in April 2023) 	
499 500 501	 Brookings GDP per capita at the city scale data (<i>Redifining Global Cities</i> 2016 report from the Brookings Institution, https://www.brookings.edu/research/redefining-global-cities/) 	
502 503 504	- World Bank GDP per capita at the country scale data (https:// data.worldbank.org/indicator/NY.GDP.PCAP.PP.CD, accessed in April 2023).).	
505 506	• Agricultural GDP and agricultural areas by country data from the FAO (https://www.fao.org/faostat/en/#home, accessed in April 2023).	
507 508 509	 Population growth scenarios from the World Urbanization Prospects – the 2018 Revisions of the United Nations (https://population.un.org/ wup/Download/, accessed in April 2023). 	
510 511 512	• Marginal costs of air pollution, noise and car accidents from the report <i>External costs of transport in Europe</i> , van Essen et al., 2019. https://trid.trb.org/view/1646234, accessed in April 2019.	
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)	
517 518 519 520	 Deloitte (report <i>The 2019 Deloitte City Mobility Index</i>, Dixon et al., 2019. https://www2.deloitte.com/content/dam/Deloitte/br/ Documents/consumer-business/City-Mobility-Index-2019.pdf, accessed in April 2023) 	
521	• Emissions datasets from the following papers:	

522 523	 Moran, D. et al. Carbon footprints of 13 000 cities. <i>Environ. Res. Lett.</i> 13, 064041 (2018). DOI 10.1088/1748-9326/aac72a.
524 525 526	 Nangini, C. et al. A global dataset of CO 2 emissions and ancillary data related to emissions for 343 cities. <i>Scientific Data</i> 6, 180280 (2019). https://doi.org/10.1038/sdata.2018.280
527 528 529 530	 Kona, A. et al. Global Covenant of Mayors, a dataset of GHG emissions for 6,200 cities in Europe and the Southern Mediterranean. <i>Earth System Science Data Discussions</i> 1–17 (2021) doi:10.5194/essd-2021-67.

Code availability

The analyses have been done using Python 3.9. Codes are available: https: //github.com/CIRED/policy_portfolios.

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543 Author Contributions

The study was conceived by C.L., V.V., and F.C. Analysis was performed by C.L., in consultation and with inputs from V.V and F.C. All authors discussed the results 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 ⁷⁷ , and the lifespan of private cars is 15 years ⁶³ . Income per capita growth scenarios are taken from the global Integrated Assessment Model IMACLIM-R ⁷⁴ and population growth scenarios from the World Urbanization Prospects of the United Nations ⁷⁵ (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/tCO2, the level required to cost-effectively reduce emissions in line with the temperature goals of the Paris Agreement ⁷⁸). 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 construc- tion 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 con- struction 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 associ- ated increase in housing prices can negatively impact inhabitants' welfare. ²⁸
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" ⁷⁷ .

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

Figure Captions

- **Figure 1.** Impact of the four policies on annual transport emissions and average 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
- 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
- mean of changes, accounting for cities' population sizes.
- **Figure 2.** Decomposition of welfare variations between different drivers in the 120 cities.
- ⁵⁵⁹ The figures represent the variation in 2035 compared to the business-as-usual
- scenario. The boxplots represent the first quartile, the median and the third
- 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
- are redistributed uniformly among the inhabitants of each city, hence increasing disposable income, while the construction of the BRT is financed by households,
- disposable income, while the constr
 hence decreasing their income).
- **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)
- in 2035, compared to the business-as-usual scenario.
- 569 See also supplementary figures S11 and S12.

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