



## LETTER

## Star-shaped cities alleviate trade-off between climate change mitigation and adaptation

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## Abstract

To deal with climate change, cities must reduce their greenhouse gas (GHG) emissions and at the same time mitigate climate impacts associated with the physical infrastructure of the built environment. One strand of literature demonstrates that compact cities of sufficient density result in lower GHG emissions in the transport and the buildings sectors compared to sprawled cities. Another strand of literature, however, reveals that compactness hinders climate adaptation by amplifying the urban heat island (UHI) effect. As a result, mitigation and adaptation objectives of cities appear to contradict each other. Here, we develop a geometrical optimization framework and model of a three-dimensional city that minimizes this conflict. It makes use of the observation that low-carbon efficient transport can be realized via linear public transport axes, and that GHG emissions and UHI effects scale differently with varying geometric properties, thus enabling design that reflects both the economics and the climate of cities. We find that star-shaped cities, in contrast to radially symmetric cities, are well suited to alleviate the problematic trade-off. We also demonstrate that urban design considerations depend on transport fuel prices. The results are of particular importance for city planners of rapidly urbanizing cities in Asia and Africa who still have the potential to shape urban layout.

## Introduction

From July to August in 2013, Eastern China suffered from a serious heat wave. As temperatures failed to fall, nearly 700 people were hospitalized due to direct heat-related illness in the coastal city of Ningbo alone (Bai *et al* 2014). During these weeks, record temperatures were observed, especially over metropolitan areas (Wang *et al* 2017). A high occurrence of heat-related morbidity in cities is no surprise: already high temperatures are exacerbated in urban regions, due to the so-called urban heat island (UHI) effect (Oke 1973). Chinese cities, similar to their counterparts in other regions of the world, are hence motivated to plan urban areas that mitigate such heat wave events.

At the same time, municipal actors in Chinese cities are also working to mitigate climate change in their cities (Westman and Broto 2018). In fact, urbanizing regions in Asia, and especially China, will play an important role for climate change mitigation due to

their scale and their ability to still influence urban planning (Dhakal 2009, Creutzig *et al* 2016).

Unfortunately, urban form that reduces greenhouse gas (GHG) emissions conflicts with urban form that reduces the UHI effect. Studies unambiguously demonstrate that more compact cities reduce not only urban transport but also building GHG emissions (Mindali *et al* 2004, Baur *et al* 2013, Baiocchi *et al* 2015, Creutzig *et al* 2015, Borck and Brueckner 2018)<sup>4</sup>. Hence, it seems that the goal of low-carbon cities (compact cities) contrasts with the goal of cities that are resilient to heat waves (non-compact cities). In other words, there is an apparent trade-off between climate change mitigation and adaptation, specifically between heat experienced and urban transport GHG emissions.

<sup>4</sup> The advantages of low emissions in direct energy use may be compromised by high emission consumption decisions of inner-city residents, as implied by a Helsinki case study (Heinonen *et al* 2013a, 2013b).

There is, however, a possible solution. For transport and UHI, the precise compactness issues are different. For low-carbon transport, it is important to have short distance, high street connectivity, and sufficiently high population density to support massive public transit systems (Bongardt *et al* 2013, Ewing and Cervero 2017, Stevens 2017). For the UHI, compactness is measured as fractal dimension, and cities that have low fractal dimension and high anisotropy—stretched rather than circular cities—display a lower UHI (Zhou *et al* 2017), even as a multitude of other local climate factors remain equally important (see [appendix](#)). This distinction points to opportunities to balance the apparent trade-off, and led us to ask how urban form could be designed to lower both transport GHG emissions and the UHI effect simultaneously.

In response to this dilemma, we posit that star-shaped cities, organized around linear transport axes, can simultaneously address the conflicting constraints imposed by UHI and transport GHG emissions, if well-designed. We take inspiration from the city of Curitiba, Brazil, which has been developed along high-density linear transport axes, while maintaining green spaces and natural parks between and around these settlement structures (Rabinovitch and Leitman 1996). A similar design also provides the necessary density and level of amenity to move away from car-dependency in cities (Newman and Kenworthy 2006).

In the following, we first review geometric consideration of urban design, before introducing our simple urban economic model. This allows us to explain the computation of transport GHG emissions and the UHI effect. We find that UHI and urban transport GHG emissions are a function of transport costs and the number of linear transport axes. We then discuss the empirical relevance of our findings and offer two contrasting examples—Curitiba and Houston—to discuss how different types of cities can respond to the coupled climate mitigation and adaptation challenge.

### Background: geometric considerations of urban design

We start with outlining geometric considerations of cities that are relevant to inform our model. For this, we consider transport GHG emissions, and UHI effects as relevant dimensions. Notably, mitigation of UHI sits at the intersection between climate change adaptation and mitigation. Reducing urban heat effects belongs to adaptation. But some strategies, such as air conditioning, heat up urban space, which in turn further augments demand for air conditioning, and consequently increase underlying energy use and GHG emissions. Hence, urban planning based strategies to reduce urban heat effects simultaneously

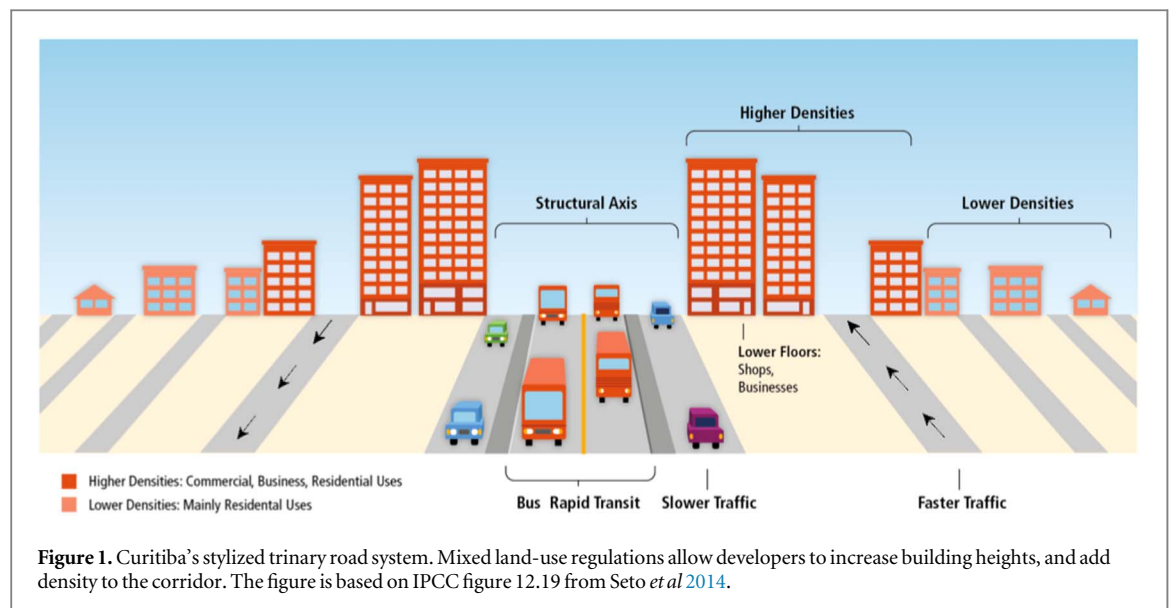
support climate mitigation and adaptation (compare with Georgescu *et al* 2015).

#### Rationale for linear transit axes

Mass rapid transit (MRT) is the most efficient means of transport in a city. However, MRT requires high infrastructure investments and is only financially viable where sufficiently high population density supports high ridership (Cervero 1998, Creutzig 2014). From this understanding, urban economic models demonstrate that inner-city transport should be dominated by MRT, unless very low gasoline prices enable a hollowing out of city centres (Fujita 1989, Creutzig 2014). Urban economic models, however, commonly assume a radially symmetric city, the so-called monocentric model, ignoring that MRT is organized along linear axes, providing unequal access not only with radial distance but also with circular angle. A monocentric model also contrasts with the intuition of urban planners, who prefer high population density along linear MRT axes but low density away from these axes. Surprisingly, these kinds of considerations are absent in the standard literature on the economics of urban transport (Small *et al* 2007).

While linear transit axes can be found in cities world-wide, a few examples stand out. Copenhagen, Denmark, is well known for its finger plan of public transit and its transit-oriented development (Knowles 2012). Similarly, the example of Curitiba, Brazil, illustrates the benefits of developing the city along structured transport axes. In the 1970s, at a time of rapid urban expansion, city planners in Curitiba decided to prioritize meeting the population's mobility needs over individual motorized transport (Rabinovitch 1992). The city's development followed a master plan, which had five key principles (Friberg 2000): (i) change the radial urban growth trend to a linear one through integrated land use, road network, and transport strategy; (ii) reduce congestion in the city centre and preserve its historical buildings and neighbourhoods with legislation and economic incentives; (iii) control and manage demographical development; (iv) support urban development with economic measures; and (v) improve infrastructures.

The first principle led to the concurrent establishment of linear structural axes. Each axis has a threefold hierarchy, as illustrated in figure 1 (Rabinovitch 1992): the central road has two exclusive bus lanes for express buses, called bus rapid transit (BRT). The reason for the choice of buses—rather than trams or subways—is the significantly lower initial investment costs. Adjacent to these are two local roads. One block away, one on each side, are high capacity free-flowing one-way streets, one for traffic flowing into the city, the other for traffic flowing out of the city (Rabinovitch 1992). Land-use regulations encourage high density along these axes. By the turn of the millennium, Curitiba had been following this plan for 30 years. The benefits had



become manifest: While being the city with the highest number of cars per capita amongst major Brazilian cities (Rabinovitch 1992), Curitiba also has the highest share of commuters using public transport (75% on weekdays) and its fuel consumption is 30% lower than in eight comparable Brazilian cities (Friberg 2000). Curitiba also preserved green spaces with an environmental program that greatly increased the number of parks and forested areas within the city (Gandara and Mills 2016)<sup>5</sup>.

### UHI geometry

Urban form characteristics partially explain the UHI effect (Zhou *et al* 2017, Xu *et al* 2019). An UHI is an urbanized area that is significantly warmer than its surrounding rural areas (see appendix). This phenomenon emerges from the thermal bulk properties and radiative forcing of urban sealed surfaces, such as asphalt, but also from the waste heat generated in cities, e.g. from automobile exhaust and air conditioning, but also from local climate conditions.

Urban form decisively shapes the UHI. From a macro perspective, the UHI scales with the logarithm of population size (Oke 1973). More specifically, powerful land-use data and computed metrics further reveal geometric features relevant to the UHI, such as city size, compactness, and anisometry (Zhou *et al* 2017).

Unsurprisingly, the bigger a city, the more intense the UHI. Also, more compact cities have higher UHI. As a measure for the compactness of a city, the study authors use the city's fractal dimension, a measure of how much the urban boundary line approaches being a two-dimensional object (approaching fractal

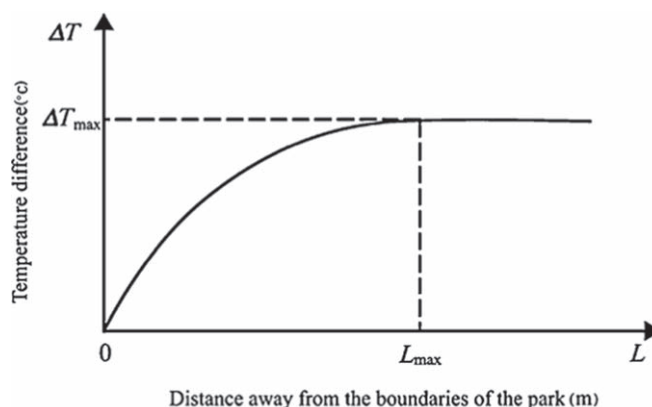
dimension 2) or a one-dimensional object (approaching fractal dimension 1).<sup>6</sup> The higher the fractal dimension, the more compact the city. The empirical analysis also showed that higher fractal dimension correlates with higher UHI intensity, suggesting a more compact city heats up more (see appendix for a qualifying view).

Another measure is anisometry: if an ellipsis is circumscribed around the city, the anisometry is the ratio of its major to its minor axis. The cited study (Zhou *et al* 2017) finds that the smaller this ratio, the stronger the UHI. This means that the more circular the ellipsis is, the stronger the UHI is too. In summary, the UHI is fuelled by larger cities with more population that are compact and round, while linear cities stay cooler, in the absence of other environmental or social forcing factors (as discussed in the appendix).

This macro perspective correlates with a micro-perspective that emphasizes different metrics and investigates what kind of park variables have what kind of impact on cooling the surrounding urban landscape. A key result of these studies is that cooling effects reach into urban surroundings as long as the park's width (Spronken-Smith and Oke 1998). Specifically, the difference between average temperature in the park  $T_{Park}$  and temperature away from the park at distance  $L$  increases up to the maximal cooling distance  $L_{max}$  (Cheng *et al* 2015, Lin *et al* 2015), as depicted in figure 2. This observation allows us to model the specific spatial dimension and geometric properties of a city on the UHI effect.

<sup>5</sup> Curitiba's success story unfortunately is compromised by newly arising social exclusion, water pollution, and problematic public transport planning, partially enabled by the predominant narrative of its sustainable transport case, preventing institutional change (Martínez *et al* 2016).

<sup>6</sup> This might suggest a neglect of the three-dimensional aspect of cities, yet compactness and density must not be confused here. While compactness measures, among other things, the ratio between built-up space and non-built-up space, density metrics measure the number of inhabitants or jobs per unit area; higher density is usually achieved by both reduced area per person, and higher buildings. Thus density metrics also translate into a three-dimensional profile of the city (Fujita 1989, Lemoy and Caruso 2018).



**Figure 2.** Temperature difference  $\Delta T$  between park temperature and built-up area temperature increases as a monotone function of distance, up to the maximal cooling distance  $L_{\max}$ , after which the park does not cool the city any more. Reprinted from Lin *et al* 2015, Copyright 2015, with permission from Elsevier.

### Model mechanics: optimizing a star-shaped city

The investigated geometric considerations suggest that a city structured along linear transport axes might address both climate mitigation and adaptation concerns. We now proceed to model a star-shaped city, organized along radially outward pointing transport axes, and to compute the trade-off between UHI and urban transport GHG emissions. The key idea of the star-shaped city is its potential for reduced compactness (high accessibility to green areas reducing the UHI) combined with high density (along transit corridors, enabling low-carbon transport).

As instrumental variables, we compute the resulting UHI effect integrated over all built-up area based on the park cooling model and total transport-related GHG emissions. We then optimize the number of axes as function of the relative importance of climate mitigation (GHG emissions from transport) and climate adaptation (lowering the UHI). Finally, we consider the role of marginal transport cost, a crucial urban economic variable shaping urban form.

#### Transit geometry

The example of MRT that we are working with in this study is BRT (Cervero and Dai 2014), corresponding to the Curitiba example. BRT is a high capacity MRT system, but at much lower financial requirements compared to, for example, a subway system.

Length and width are the key geometric properties of the linear transit axis. We model a city that encourages settlements near the transit axis, while aiming to preserve green spaces in between. With public transport serving the axis, a restriction on the width of settlement on either side of a transport axis comes from the acceptable walking time to a public transport stop. If 10 min is an acceptable time for this walk and if average walking speed is  $4.5 \text{ km h}^{-1}$ , then the maximum acceptable distance to walk is 800 m (Bertaud 2004).

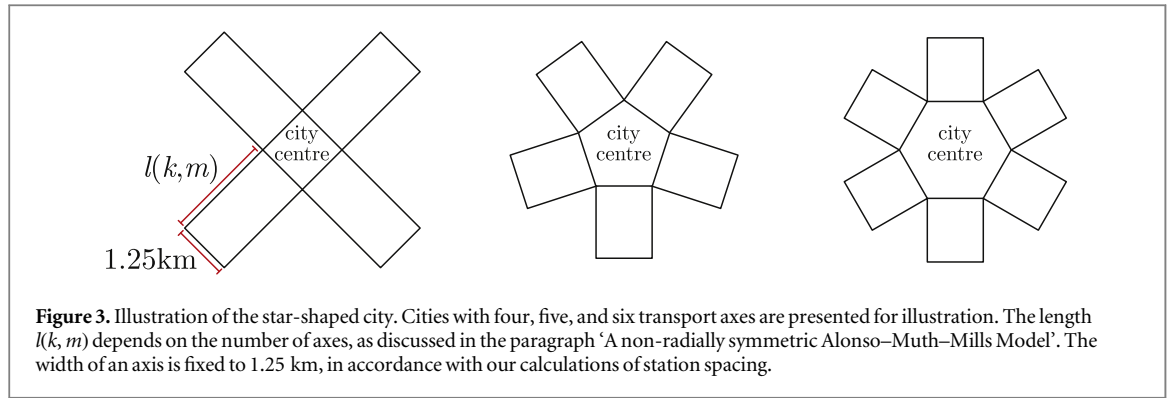
The actual spacing of bus stops for different cities around the world ranges from 200 to 600 m (Ibrahim and Isma'il 2013). As there is a trade-off between ease of access and speed of transport, the optimal bus stop spacing depends on the structure of the city and the kind of transport. For a BRT system, average station spacing in North America ranges from 0.32 km (Cleveland) to 5.28 km (Halifax) (APTA Bus Rapid Transit Working Group 2010). These distances include express portions of the system (with a maximal spacing of 12.4 km between two stops for Halifax). In Curitiba, the average residential location is less than 200 m from the next regular bus stop, but on average 1850 m away from the next BRT station (Hino *et al* 2014). However, these stations are highly attractive: the presence of at least two BRT stations within 500 m radius induces significantly higher walking than in the case without BRT station (Hino *et al* 2014).

To calculate an adequate width of linear transit axes, we consider a transit stop spacing of 1000 m along the transit axis. Then the furthest point from any station is given by

$$\sqrt{\left(\frac{1000}{2}\right)^2 + x^2} = y, \quad (1)$$

where  $x$  is the uniform width of the axis. Now, supposing that there is a diagonally walkable path from this point,  $y \leq 800 \text{ m}$  allows residents to reach a transit station in 10 min (see above). Solving for  $x$ , we find that:  $x = \sqrt{(800^2 - 500^2)} \approx 625 \text{ m}$ . Consequently, if stations are spaced at 1 km along the transit axis and there are diagonal streets linking these stations to the furthest points (which correspond to the corners of the square with side length 1000 m centred at the stations), then the distance of transit axis to green space is 625 m. This is illustrated in figure 3, where the total width of the axis is 1.25 km, independent of the number of axes. In contrast, the length of the axis, as illustrated in figure 3, depends on the number of axes  $k$ , as discussed in the paragraph below, and the transport costs  $m$ .





### A non-radially symmetric Alonso–Muth–Mills (AMM) Model

Our study is based on the classical monocentric urban model of AMM (Fujita 1989), which we modify by imposing linear transport axes, as inspired by Curitiba (figure 3), instead of radial symmetry. The AMM model assumes a unique city centre, to which all residents commute. It is described in detail by Fujita (1989) and summarized by Lohrey and Creutzig (2016) as follows: all residents have the same, fixed income  $Y$ , which they spend on transport costs  $m(r)$ , rent  $R(r)s(r)$ , and bread-consumption  $z$ . This gives the constraint:

$$Y = z + R(r)s(r) + m(r), \quad (2)$$

where  $r$  is the distance from the city centre,  $R(r)$  the per-area rent, and  $s(r)$  the dwelling space. Note that  $m(r)$  is linear in radial distance, i.e.  $m(r) = nr$  for some constant  $n$ . The utility function is maximized by the residents and supposed to take a log-linear form (Fujita 1989):

$$U(z, s) = \zeta \log(z) + \eta \log(s) \quad \text{with} \quad \max U(z, s). \quad (3)$$

This is a Cobb–Douglas function that satisfies a set of assumptions about the utility function: it is continuous, increasing for all  $z > 0$  and  $s > 0$ , and all indifference curves are strictly convex and smooth (Fujita 1989). In the case of a closed city, i.e. constant urban population  $N$ , bid rent  $\Psi(r)$  and population density  $\rho(r)$  are described as:

$$\Psi(r, u) = \zeta^{\frac{\zeta}{\eta}} \eta (Y - m(r))^{\frac{1}{\eta}} \exp\left(-\frac{u}{\eta}\right) \quad (4)$$

$$\rho(r, u) = \left[ \zeta^{-\frac{\zeta}{\eta}} \eta (Y - m(r))^{-\frac{\zeta}{\eta}} \exp\left(\frac{u}{\eta}\right) \right]^{-1}. \quad (5)$$

In this model, the utility  $u$  is constant over  $r$  and can therefore be dropped. The transport costs  $m(r)$  are purely pecuniary costs. The bid rent  $\Psi$  is defined as the maximum rent per unit of land the household can pay for residing at distance  $r$  while having utility  $u$  (Fujita 1989). It is assumed to be equal to per-area rent  $R$  (Fujita 1989, Lohrey and Creutzig 2016). We use  $m(r)$  for transport costs if we want to stress dependence

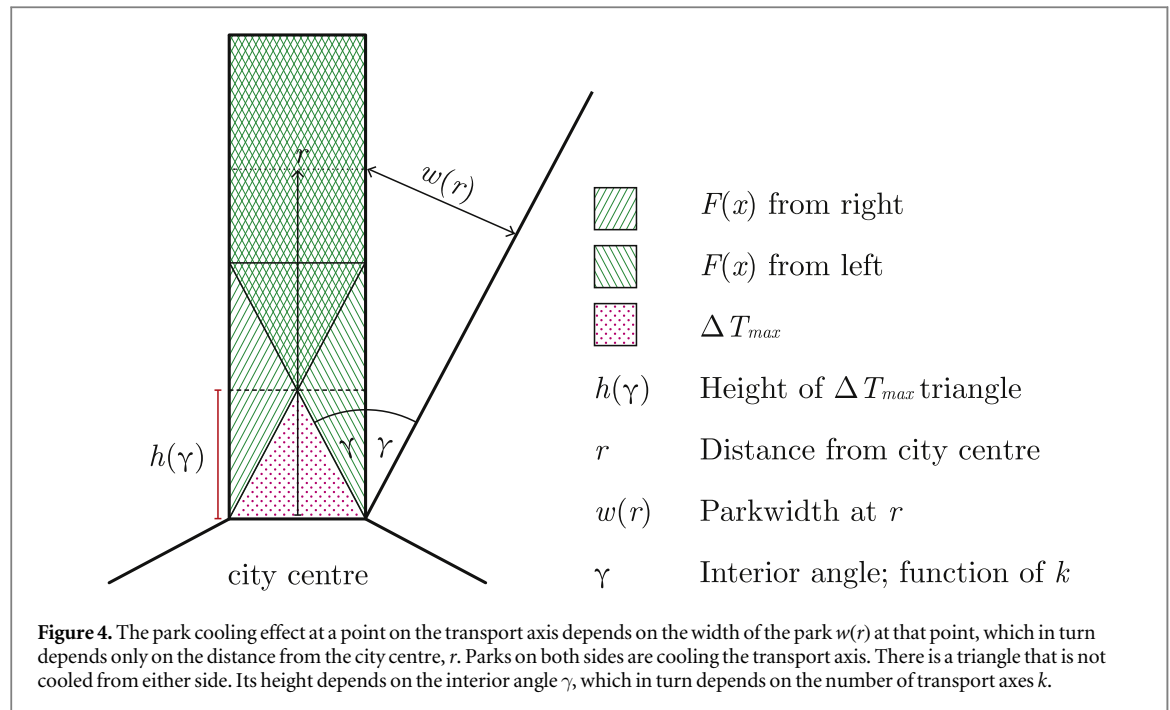
on the distance from the city centre, but most of the time we will simply use  $m$ .<sup>7</sup>

To calculate the population density  $\rho$  in this modified model, we assumed that, for a given number  $k$  of axes, each axis would host an equal fraction  $N_k$  of the overall population  $N$ . That is:  $N_k = \frac{N}{k}$ . This means that no residents live in the city centre, corresponding to the idea of the city centre as a central business district typically assumed in AMM models. The AMM model with radial symmetry allows us to determine urban radial extension. With linear transport axes, radial symmetry is lost and the residents have to be distributed accordingly onto the linear axes, subject to the density function. As result, both the number and length of axes are endogenous to transport costs and weighting of UHI. This is calculated through an iterative process. With a fixed width, fewer transport axes mean less space onto which the residents can be distributed and the axes therefore have to be longer. Accounting for this difference to the radially symmetric AMM model, we followed the same iterative method as in Lohrey and Creutzig (2016). The model is based on code originally written by Steffen Lohrey and can be found [here](#).

### Modelling UHI

We make use of the empirical insights discussed in the previous section to design a model of micro-scale UHI as a function of location and distance to green area. With the description from (Lin *et al* 2015) (visualized in figure 2), we fit a curve to the data from Cheng *et al* (2015), which provides the maximal temperature difference together with the maximal cooling distance. We find a function  $F$  that describes how the temperature increases away from the park. The cooling extent depends on the size of the park and corresponds roughly to the width of the park. While wind direction has a non-negligible influence on the cooling extent, we omit this aspect in favour of simplification (but see the [appendix](#) for details). We specifically assume that  $L_{\max} = w(r)$  where  $w(r)$  denotes the width of the park at any point on

<sup>7</sup> Fujita (1989) uses  $T(r)$  for the transport costs, but to avoid confusion with the temperature  $T$  in our text, we have opted for  $m(r)$ . Similarly, in our description of the AMM model, we have chosen  $\zeta$  and  $\eta$  where Fujita (1989) uses  $\alpha$  and  $\beta$ .



the transport axis at distance  $r$  from the city centre, as illustrated in figure 4. Due to symmetry, any point on the transport axis at distance  $r$  from the city centre can be express as  $Q = (x, r)$ . Then, the  $x$ -coordinate indicates how far  $Q$  is from the closest park. Consequently, we obtain the following function  $H$  for the UHI effect:

$$H(Q) = H(r) = \begin{cases} F(x, r) & \text{if } \|x - \frac{\omega}{2}\| \leq w(r), \\ \Delta T_{\max} & \text{otherwise} \end{cases} \quad (6)$$

where  $\Delta T_{\max}$  denotes the maximum temperature difference between city and rural area and  $\omega$  denotes the width of the transport axis. At the same time, a general, exponential temperature decay away from the city centre can be observed (Zhou *et al* 2015). In our case, this decay happens along  $r$ -direction, the temperature decays exponentially. The function  $F(x)$  then takes the form:

$$F(x, r) = (\Delta T_{\max} - (\nu \log(x) + \mu)) \times \Delta T_{\max} \exp(-Sr).$$

$F$  is thus the combination of the two cooling effects: in the  $x$ -direction it is the park cooling effect, where the values for  $\nu$  and  $\mu$  are obtained through the curve fitting explained above. In the  $r$ -direction it is the exponential decay away from the city centre.

Basic trigonometry allows us to express  $w(r)$  as a function of the interior angle  $\gamma$ , which in turn depends on the number of axes  $k$ . In this way, we obtain a relationship between the UHI effect and the number of transport axes. With an increase in the number of transport axes, the park size and in particular the park width decreases. Therefore, as illustrated in figure 4, the cooling extent decreases thereby augmenting the UHI effect.

At the city centre edge of the transport axes, there is a part that is not entirely cooled by the park

(figure 4). While the vertical sides of the transit axes are cooled by the park (here  $F(x)$  applies),  $h(\gamma)$  denotes the part of the axis that is not entirely covered by the cooling effect. Note that since  $\gamma$  depends on the number of axes  $k$ , so does  $h$ . In particular, the higher the number of axes, the smaller  $\gamma$  and hence the larger  $h(\gamma)$ . The triangle dotted in red in figure 4 is not cooled at all, denoted with  $\Delta T_{\max}$ .

### Calculating emissions from transport

The total transport emissions in the city are calculated after Lohrey and Creutzig (2016) as

$$C_{CO_2} = k \int_0^l r \rho(r) dr. \quad (7)$$

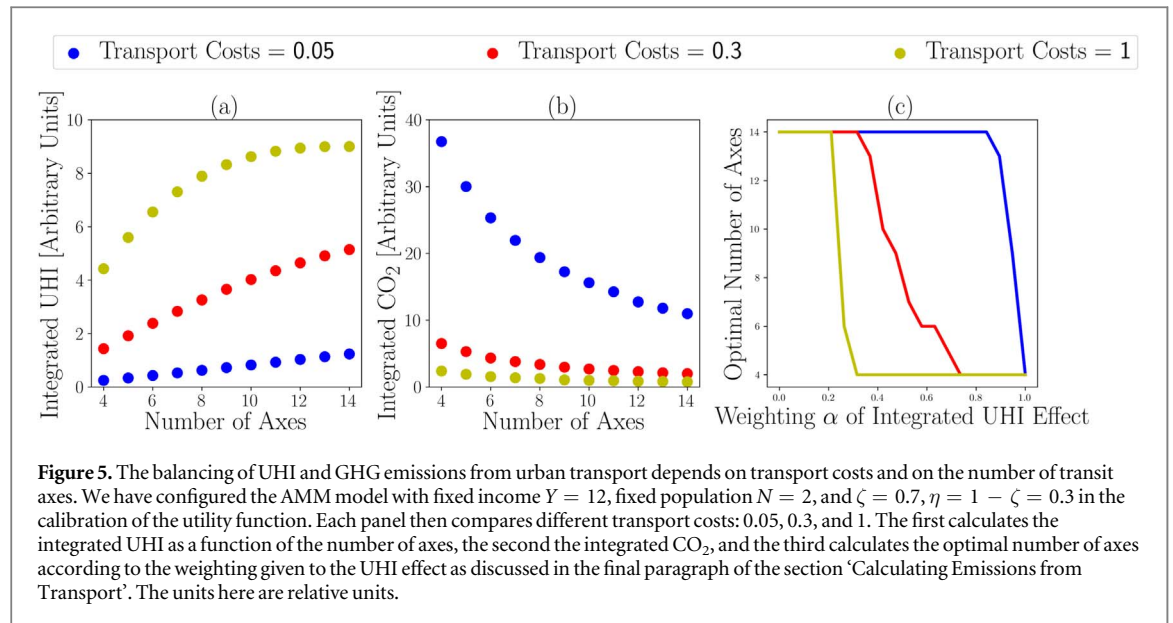
In this model the relevant factors are: (i) length of axes  $l$ ; with constant population  $N$ , the length of axes depends on the number of axes; (ii) number of axes  $k$ ; and (iii) density profile  $\rho(r)$ . We assume a direct commute along the transport axes to the city centre, ignoring the time costs of walking (which are endogenously compensated by lower residential costs).

We can then calculate the total UHI effect (abstracting from wind direction, local vegetation cover, and other specific effects) along an axis by integrating the function of equation (6) over the entire axis. Thus we have:

$$H_{\text{tot}} = \int_1^{r_c} \int_0^\omega H(x, y) dx dy. \quad (8)$$

Here,  $r_c$  is the outer limit of the city, and  $\omega$  denotes the width of the axes. The integral starts at 1, as we are only calculating the UHI effect along an axis here, not in the city centre.

To compute the overall total UHI for the entire city, we simply add the number of axes times the axis-specific UHI effect in equation (8) plus the UHI effect in



the city centre. The UHI in the city centre is assumed to be constant via the above formula for  $H(Q)$  and depends only on the area of the city centre. Note that an increase in the number of arms  $k$  means an increase in the area of the city centre, since this is assumed to be a regular  $k$  sided polygon with side length 1.25 km. This sum gives us  $H_{\text{int}}$ , the UHI effect in the city.

Having calculated the accumulated UHI effect, we need to normalize with respect to area to measure the average UHI effect felt:

$$H_{\text{int}} = \frac{kH_{\text{tot}}}{A}. \quad (9)$$

Here,  $A$  is the Area of City, which denotes that part of the city that is actually built-up, including the axes and the city centre, but not the parks in between the axes. Since the density profile  $\rho$  depends on the costs of transport, we ran the calculations for various values of transport costs. The results can be seen in figure 5. As is expected, more transport axes result in an increased integrated UHI effect. At the same time,  $\text{CO}_2$  emissions are reduced by more transport axes. Increased transport costs mean more people will locate closer to the city centre, and population density increases. The calculations reflect that if the transport costs are higher, overall  $\text{CO}_2$  emissions are lower and integrated UHI is higher for the same number of transport axes.

In order to determine the optimal number of transport axes, we use the optimization function:

$$G(k, m) = \alpha H_{\text{int}} + \beta C_{\text{CO}_2}. \quad (10)$$

Because both  $H_{\text{int}}$  and  $C_{\text{CO}_2}$  depend on the number of axes  $k$  as well as on the transport costs  $m$ , this function does as well. The factors  $\alpha$ ,  $\beta$  weight the relative importance of UHI reduction (climate adaptation) and transport energy reduction (climate mitigation), respectively, with  $\alpha + \beta = 1$ .

### Results: optimal number of transit axes

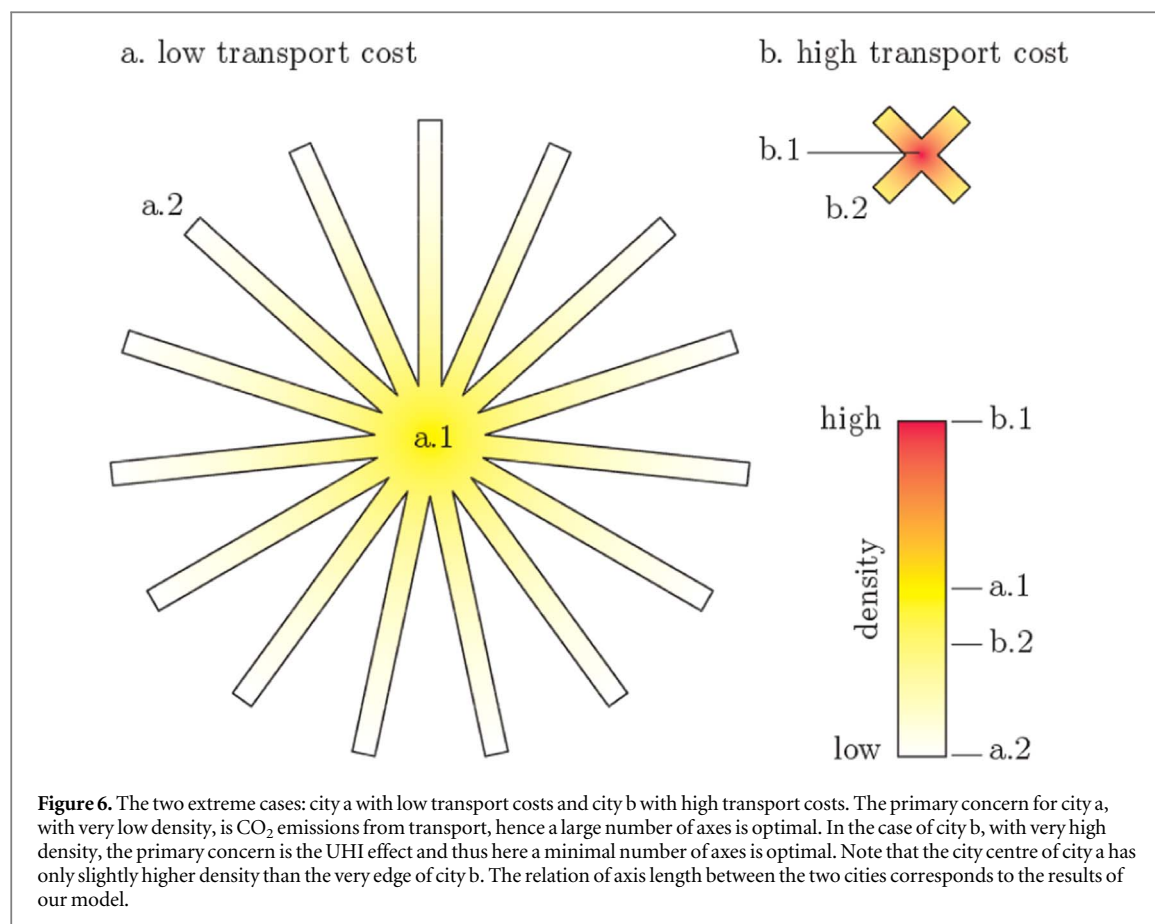
Here we show that the number of transit axis (provided that population is constant) impacts UHI and GHG emissions from transport. Optimal city design, inversely, involves the number and length of transit axes as a crucial consideration.

Firstly, both UHI and transport emissions change with the number of axes. Specifically, with more transit axes, the UHI increases (figure 5(a)), while total GHG emissions decrease (figure 5(b)).

Secondly, we calculate how the optimal number of axes changes as a function of the weighting factor  $\alpha$  for several values of  $m$  (figure 5(c)). This is done using the optimization function in equation (10) with several values of  $m$  ( $m = 0.05, 0.3$ , and  $1$ , respectively). We take twenty equally spaced values for  $\alpha$  between 0 and 1 and calculate the sum in equation (10). For a fixed  $m$  and a fixed  $\alpha$ , we compare the results for each number of axes  $k$ . The  $k$  with the lowest  $G(k, m)$  then gives us the optimal number of  $k$  for a given  $m$  and a given  $\alpha$ . A higher value of  $\alpha$  means that the UHI effect becomes more important. Consequently, the ideal number of axes is lower. Conversely, with low  $\alpha$ , the UHI effect is negligible and the optimal number of axes increases to minimize  $\text{CO}_2$  emissions from transport.

Transport costs play a crucial role. With high transport costs and thus high density, the UHI effect is the most significant, while the  $\text{CO}_2$  emissions are at their lowest. Conversely, with low transport costs and thus low density, the  $\text{CO}_2$  emissions rise. This is reflected in the last panel, where for the low-density city the UHI effect has to be weighted very highly (at 0.9) for the city to reduce the number of axes and to mitigate the UHI effect.

An interesting observation is that the model prefers many or few axes, depending on the relative importance of climate adaptation and mitigation, but that an intermediate number of axes are rarely observed.



Urban density is the crucial intermediate factor communicating the effect of urban design on climate mitigation and climate adaptation dimensions. In our models, urban density is controlled not only via the number of transport axes but even more dominantly through the costs of transport: the higher the costs, the denser the city, and with higher density, CO<sub>2</sub> emissions are significantly reduced. The UHI effect behaves in the opposite way: with higher density we have a higher integrated UHI effect. Importantly, transport costs have more impact causally than the numbers of transport axes at any fixed transport costs. This observation translates into two extreme cases, one city with low transport cost and one with high transport costs (figure 6).

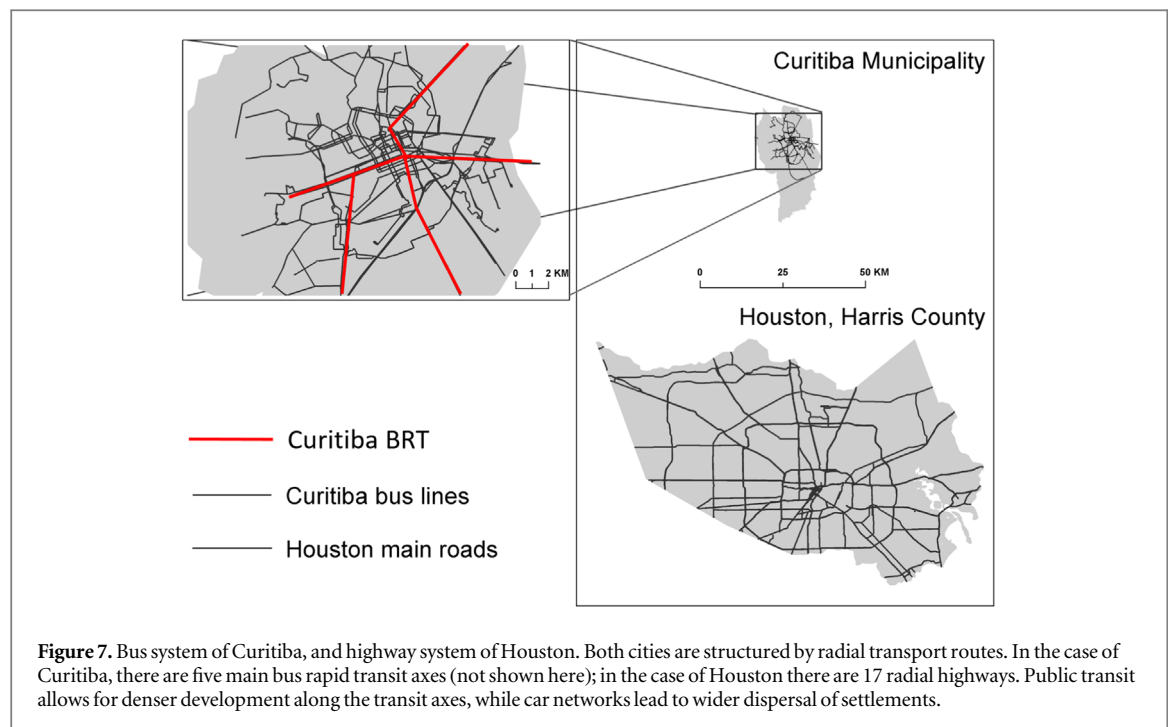
Transport costs crucially influence the density profile, and thereby the three-dimensional shape of the cities. As can be seen in the figure, low transport costs imply an extended city while high transport costs imply a compact, dense city. For these extreme cases, the point of maximal density in the low transport cost city (a.1) is just marginally more densely populated than the point of minimal density in the high transport cost city (b.2). This, together with the distance between points a.1 and a.2 as well as b.1 and b.2 (that is, the points of maximal and minimal density of each city) on the legend gives a sense of the three-dimensional shape of the city. With low transport costs, the city centre is characterized by medium density. This density is slowly decaying as one moves from the centre to the fringe of

the city, which is not densely populated at all. In contrast, with high transport cost the city centre is very densely populated, yet over a short distance the density decays rapidly to a medium density on the fringe.

These two extreme cases can be exemplified by Houston and Curitiba. Houston, while occupying a large area, has small orographic and topographic variation. Elevations of the built-up area range from 8 to 30 m above mean sea level, with only slight undulations in the average gradient. Other important factors for urban climate and the relevance of the UHI are the prevailing wind conditions, specifically whether wind is coming from the gulf or from the interior. Also, local air pollution dominates along the ship canals, where heat and pollutants react in ozone formation (Johnson *et al* 2014). The Houston case served as a test bed to demonstrate that UHI can be captured with satellite radiance data (Streutker 2002).

Houston exemplifies a city with low transport costs, corresponding to the paradigmatic example of the car-dependent city. Individual transport is cheap, and inhabitants can instead spend income on living space. This means that the city spreads further and as a consequence becomes less dense. Figure 7 shows the city structured by highways. There are more than 10 axes, which are connected by one small and one large ring highway. Such a city has already, due to an overall low density of 242 residents km<sup>-2</sup> in the metropolitan area, a low UHI effect. Therefore, the





reduction of CO<sub>2</sub> emissions becomes the primary concern. We can see this in figure 5: for low transport costs, the point at which reducing the CO<sub>2</sub> emissions stops being the main concern is only for a very high value of  $\alpha$ . In other words, we have to value the reduction of the UHI effect very highly for it to become more important than the reduction of transport emissions. Consequently, such a low-density city would best be served with providing a high number of transport axes, as is illustrated in figure 6(a).

Curitiba has a slightly higher variance in elevation than Houston, ranging from approximately 850–975 m above sea level and averaging at roughly 935 m. An important local factor for the urban climate in Curitiba are the structural sectors imposed by the master plan guiding the development of the city. These corridors have an impact on ventilation and daylight accessibility. Consequently, challenges include thermal discomfort as well as possible effects on air quality (Krüger *et al* 2011, Krüger and Tamura 2015). Because of relatively cold temperatures in the city during winter months, the UHI at that time positively affects thermal well-being.

Curitiba exemplifies a city with a different urban design, oriented along BRT (figure 7) and resulting in higher transport costs in time for individual motorized modes. Even though it is the fourth richest city of Brazil, Curitiba has only one third of the per capita income of Houston, and hence inhabitants have less opportunity to purchase large housing space. Curitiba has a high population density of 4062 residents km<sup>-2</sup> = 40 residents ha<sup>-1</sup>.

In figure 7, the city centre is clearly discernible, together with four major axes (the two southern ones have been joined at the end). To reduce expenses, both in terms of time and money, individuals prioritize

residential location that are attractive for commuting with public transit, in turn reinforcing a more compact urban form. As the travel distances are low in this high density city, the main concern quickly becomes the UHI effect. Figure 5 demonstrates that when transport costs are high, already a low value of  $\alpha$  suffices to reduce the optimal number of axes. Therefore, such a city is best served with a low number of transport axes as illustrated in figure 6(b).

This comparison verifies that the main geometric properties of our model make sense. Curitiba has higher relative transport costs (given that per capita income is much lower), higher density, less area demand, and a smaller number of axes (5). In contrast, Houston has low transport costs, low population density, more area demand, and a higher number of transport axes (17). While Curitiba municipal policy makers intentionally designed its geometry with goals that are at least in alignment with climate change action, Houston did not. If Houston municipal policy makers prioritize climate change mitigation, they would charge automobile drivers. Curitiba is well advised to continue its policy of green area preservation to avoid increasing the risk of deadly urban heat waves.

## Conclusion

Future-oriented urban planning needs to tackle the challenges of both climate mitigation and adaptation, goals that can be conflicting: more compact urban form reduces GHG emissions from transport, but increases urban heat stress, one of the deadliest consequences of climate change. Here we build a geometric model of urban design, informed by urban

economics, that reveals a strategy to relax this trade-off: building star-like cities along linear transit axes. A higher number of axes will tend to mostly support climate mitigation, whereas a lower number of axes are conducive to reducing urban heat stress.

However, the underlying urban transport costs, both in time and monetary terms, remain a dominant factor in shaping urban form and resulting climate effects.

Our modelling results have several empirical correlates. (A) UHI is reduced by less compact, and more linear cities (Zhou *et al* 2017); (B) Green areas have a cooling effect radiating into surrounding built-up areas (Cheng *et al* 2015, Lin *et al* 2015); (C) urban economic models can replicate the distribution of cities with respect to population density and modal share as a function of transport costs (Newman and Kenworthy 1989, Creutzig 2014); (D) the effect of fuel prices on urban GHG emissions is empirically verified across a sample of 274 cities world-wide (Creutzig *et al* 2015). However, there is scope for empirical studies that use emerging big data on cities (Nangini *et al* 2019) to investigate the geometric features of cities and their relevance for climate mitigation and adaptation in more detail (Ilieva and McPhearson 2018, Creutzig *et al* 2019). In particular, combining remote sensing data with data on transport activities and temperatures at high spatial resolution for a number of cities that are comparable in terms of climate and socio-economic characteristics, will make it possible to disentangle the relevance of urban planning for climate change mitigation and adaptation. This will also help to overcome data limitations underlying this study, such as relying on a cooling decay function derived from observations from Shanghai only (Cheng *et al* 2015, Lin *et al* 2015).

Other social and environmental dimensions, such as air pollution and congestion are equally important in the design of cities. Air quality would profit from linear public transit axes, but high population density might be harmful, as it increases the fraction of pollutants breathed in (Lohrey and Creutzig 2016). Congestion might become worse, if considerable car traffic is routed via linear transit axes. Access to green spaces, a local quality of life dimension going beyond moderation of the UHI effect, however, would most likely improve. A complicated question involves consumption-based emissions. Residential living in dense inner-city areas in Helsinki has been associated with higher emissions from air travel (Heinonen *et al* 2013a). In the star-shaped city, dense residential living along the transit axes is associated with pedestrian access to green areas. Possibly, such access to green space counterfactually reduces air travel, a consideration that opens avenues for further research.

Our results are particularly important for rapidly urbanizing and developing cities, most of which are located in Asia and Africa (United Nations 2014), with more than 90% of urbanization-related GHG emissions until 2050 expected to come from these world

regions (Creutzig *et al* 2015, 2016). Countries like China, India, Vietnam, and Nigeria differ in their specific urbanization dynamics and political environment, and hence there is no straightforward upscaling strategy for building star-shaped cities. However, a few tentative directions can be given.

First, many Asian cities are clogged with congestion and air pollution, and overmotorization is a key political issue. While climate change mitigation itself is not the main motivation, the local environmental concerns make alternative strategies to car and motorcycle centred urban mobility more attractive (Krzyżanowski *et al* 2005). Heat waves are a lethal danger to livelihoods in many African countries and South Asia (Mora *et al* 2017). Cities like Beijing are studied intensively both from the perspective of transport GHG emissions and UHI effect (Creutzig and He 2009, Miao *et al* 2009, Wang *et al* 2016). Hence, there is considerable attention and motivation to alleviate the urban climate challenges.

Second, any implementation strategy is likely to meet rapid urbanization dynamics that are hard to steer and control. It may be important to use price instruments, such as fuel taxes, to incentivise decentralized solutions that are more compatible to a public transit star-shaped city.

Third, the academic focus of both transport GHG emissions and UHI effect in Beijing may raise awareness of these issues especially in the Chinese capital, which in turn could facilitate upscaling of successful urban planning strategies. Importantly, Chinese cities and regions often follow the lead of successful example cities—a strategy dubbed the isomorphism of local development policies (Chien 2008), which has also been suggested to upscale low-carbon transport policies in China (Creutzig *et al* 2012). In fact, national policies already promote urban development that is consistent with climate mitigation and adaptation goals, and that could evolve into the design of star-shaped cities (Normile 2016). In India, cities grow more organically and unplanned. However, there is a growing and dynamic interest in providing policy frameworks that could facilitate the development of cities along transit axes (Ahluwalia *et al* 2014).

Fourth, Asia is at the forefront of development and financing models of transit-oriented development. In particular, Singapore and Tokyo have long-standing experience in financing the construction of high capacity mass transit axes via land value capture (Cervero 1998). This experience could also be leveraged for other rapidly developing cities in Asia and Africa.

In summary, this paper contributes to the joint negotiation of climate mitigation and adaptation concerns. It also proposes a new framework of analysis for sustainable cities, combining geometric and spatially explicit effects with urban economic modelling. We believe that this approach holds further potential for both relevant policy and intellectually stimulating research.

## Appendix: the UHI effect

Urban built environments heat up more than their rural surroundings, as building materials better absorb and store solar irradiation. Urban areas also often lack relevant cooling resulting from evaporation by vegetation. The local urban climate modifies the UHI in various ways, including through wind conditions, through street canyons that may channel wind (Oke 1988), but that may also provide shading (Johansson 2006), through mirror effects of glass facades, and through local vegetation (Susca and Gaffin 2011). In this paper, we focus on the geometric properties of urban form, as those play an important role in determining the strength of the UHI (Zhou *et al* 2017).

The UHI is a generic term. It is more accurately differentiated in terms of surface temperature and air temperature, with the former corresponding to the temperature of the surface, as measured by remote sensing, and the latter to the temperature of the air close to the ground, usually at a height of 2 m, as measured by local climate stations air temperature is likely to be of higher importance for climate impacts (including on human health). In this study, we base our evaluation of urban form effects on the surface UHI, as the underlying study of Zhou *et al* (2017) relies on remote sensing data. However, there is a high correlation between surface UHI and air UHI (Prihodko and Goward 1997), justifying the use of surface UHI for our modelling study.

The UHI can also be differentiated in terms of diurnal and seasonal nature. A global study of 419 cities has determined that the average annual daytime surface UHI is up to 2.1 °C higher than the average annual nighttime surface UHI (Peng *et al* 2012). A different study found for European cities a maximal saturation of the UHI in summer with a mean of 3 °C (Zhou *et al* 2013). Problematically, the terms urban and rural, which are used to define the UHI, denote a great variety of landscapes. This complicates the comparison of UHI studies since heterogeneous urban and rural situations are captured under the same term (Stewart and Oke 2012). In the case of a desert city like Phoenix, Arizona, studies have observed great potential for land system architecture to address the heterogeneous nature of the urban requirements (Connors *et al* 2013, Li *et al* 2017), suggesting that compact, regular green spaces (such as grass) can help reduce nighttime surface UHI, while irregular larger spaces can help reduce daytime surface UHI (Li *et al* 2017).

Modelling and simulation studies suggest that, e.g. for US American cities urban adaptation strategies are effective (Georgescu *et al* 2014, Ward *et al* 2016). Tree planting and urban greening belong to the key strategies mitigating urban heat stress (Fernandez Milan and Creutzig 2015). Green areas are commonly more abundant in leafy suburbs, compared to built-up inner cities. More compact cities tend to increase the UHI

effect (Zhou *et al* 2017) and consequently worsen the impact of deadly heat waves (Mora *et al* 2017) (even if UHIs may often be of lower magnitude under warming conditions Scott *et al* 2018). While the UHI effect has positive effects in winter months in cities that have considerable heating demand, the impact of heat on health is emerging as one of the key and most harmful impacts of climate change (Gasparrini *et al* 2017). The concerns surrounding urban heat waves are only going to rise. Urbanization and more compact urban environments imply that a greater population is exposed to increased heat (Lemonsu *et al* 2015).

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## References

- Ahluwalia I J, Kanbur R and Mohanty P K 2014 *Urbanisation in India: Challenges, Opportunities and the Way Forward* (New Delhi: Sage Publications)
- APTA Bus Rapid Transit Working Group 2010 *Bus Rapid Transit Service Design: APTA Standards Development Program Recommended Practice* APTA BTS-BRT-RP-004-10 American Public Transportation Association, Washington, DC
- Bai L, Ding G, Gu S, Bi P, Su B, Qin D, Xu G and Liu Q 2014 The effects of summer temperature and heat waves on heat-related illness in a coastal city of China, 2011–2013 *Environ. Res.* **132** 212–9
- Baiocchi G, Creutzig F, Minx J and Pichler P-P 2015 A spatial typology of human settlements and their CO<sub>2</sub> emissions in England *Glob. Environ. Change* **34** 13–21
- Baur A H, Thess M, Kleinschmit B and Creutzig F 2013 Urban climate change mitigation in Europe: looking at and beyond the role of population density *J. Urban Plan. Dev.* **140** 04013003
- Bertaud A 2004 *The Spatial Organization of Cities: Deliberate Outcome or Unforeseen Consequence?* IURD Working Paper Series UC Berkeley: Institute of Urban and Regional Development, Berkeley, CA (<https://escholarship.org/uc/item/5vb4w9wb>)
- Bongardt D, Creutzig F, Hüging H, Sakamoto K, Bakker S, Gota S and Böhler-Baedeker S 2013 *Low-Carbon Land Transport: Policy Handbook* (Abingdon: Routledge)
- Borck R and Brueckner J K 2018 Optimal energy taxation in cities *J. Assoc. Environ. Resour. Econ.* **5** 481–516
- Cervero R 1998 *The Transit Metropolis: A Global Inquiry* (Washington, D.C.: Island Press)
- Cervero R and Dai D 2014 BRT TOD: leveraging transit oriented development with bus rapid transit investments *Transp. Policy* **36** 127–38
- Cheng X, Wei B, Chen G, Li J and Song C 2015 Influence of park size and its surrounding urban landscape patterns on the park cooling effect *J. Urban Plan. Dev.* **141** A4014002-1–10
- Chien S-S 2008 The isomorphism of local development policy: a case study of the formation and transformation of National Development Zones in Post-Mao Jiangsu, China *Urban Stud.* **45** 273–94
- Connors J P, Galletti C S and Chow W T L 2013 Landscape configuration and urban heat island effects: assessing the relationship between landscape characteristics and land surface temperature in Phoenix, Arizona *Landscape Ecol.* **28** 271–83

- Creutzig F 2014 How fuel prices determine public transport infrastructure, modal shares and urban form *Urban Clim.* **10** 63–76
- Creutzig F, Agoston P, Minx J C, Canadell J G, Andrew R M, Le Quéré C, Peters G P, Sharifi A, Yamagata Y and Dhakal S 2016 Urban infrastructure choices structure climate solutions *Nat. Clim. Change* **6** 1054
- Creutzig F, Baiocchi G, Bierkandt R, Pichler P-P and Seto K C 2015 Global typology of urban energy use and potentials for an urbanization mitigation wedge *Proc. Natl Acad. Sci.* **112** 6283–8
- Creutzig F and He D 2009 Climate change mitigation and co-benefits of feasible transport demand policies in Beijing *Transp. Res. D* **14** 120–31
- Creutzig F, Thomas A, Kammen D M and Deakin E 2012 Transport demand management in Beijing, China: progress and challenges *Low Carbon Transport in Asia: Capturing Climate and Development Co-Benefits* (London: Earthscan)
- Creutzig F *et al* 2019 Upscaling urban data science for global climate solutions *Glob. Sustain.* **2** E2
- Dhakal S 2009 Urban energy use and carbon emissions from cities in china and policy implications *Energy Policy* **37** 4208–19
- Ewing R and Cervero R 2017 Does compact development make people drive less? The answer is yes *J. Am. Plan. Assoc.* **83** 19–25
- Fernandez Milan B and Creutzig F 2015 Reducing urban heat wave risk in the XXI century *Curr. Opin. Environ. Sustain.* **14** 221–31
- Friberg L 2000 Innovative solutions for public transport; Curitiba, Brazil *Sustainable Development International* 4th edn (London: ICG Publishing) pp 153–6
- Fujita M 1989 *Urban Economic Theory—Land Use and City Size* (Cambridge: Cambridge University Press)
- Gandara J M and Mills A S 2016 Successful master plan implementation in Curitiba, Brazil, and its positive effects on urban tourism *Travel and Tourism Research Association* 2009 36
- Gasparrini A *et al* 2017 Projections of temperature-related excess mortality under climate change scenarios *Lancet Planet. Health* **1** e360–7
- Georgescu M, Chow W T L, Wang Z H, Brazel A, Trapido-Lurie B, Roth M and Benson-Lira V 2015 Prioritizing urban sustainability solutions: coordinated approaches must incorporate scale-dependent built environment induced effects *Environ. Res. Lett.* **10** 061001
- Georgescu M, Morefield P E, Bierwagen B G and Weaver C P 2014 Urban adaptation can roll back warming of emerging megapolitan regions *Proc. Natl Acad. Sci.* **111** 2909–14
- Heinonen J, Jalas M, Juntunen J K, Ala-Mantila S and Junnila S 2013a Situated lifestyles: I. How lifestyles change along with the level of urbanization and what the greenhouse gas implications are—a study of Finland *Environ. Res. Lett.* **8** 025003
- Heinonen J, Jalas M, Juntunen J K, Ala-Mantila S and Junnila S 2013b Situated lifestyles: II. The impacts of urban density, housing type and motorization on the greenhouse gas emissions of the middle-income consumers in Finland *Environ. Res. Lett.* **8** 035050
- Hino A A F, Reis R S, Sarmiento O L, Parra D C and Brownson R C 2014 Built environment and physical activity for transportation in adults from curitiba, Brazil *J. Urban Health* **91** 446–62
- Ibrahim M N and Isma'il Y 2013 Estimation bus stops spacing on public transport routes in kano metropolis using minibus stop time interval *Int. J. Eng. Sci. Invention* **2** 36–44
- Ilieva R T and McPheerson T 2018 Social-media data for urban sustainability *Nat. Sustain.* **1** 553
- Johansson E 2006 Influence of urban geometry on outdoor thermal comfort in a hot dry climate: a study in Fez, Morocco *Build. Environ.* **41** 1326–38
- Johnson G S, Washington S C, King D W and Gomez J M 2014 Air quality and health issues along Houston's ship channel: an exploratory environmental justice analysis of a vulnerable community (Pleasantville) *Race, Gender Class* **21** 273–303
- Knowles R D 2012 Transit oriented development in copenhagen, Denmark: from the finger plan to Ørestad *J. Transp. Geogr.* **22** 251–61
- Krüger E and Tamura C 2015 Urban climate studies in a subtropical location: literature review and current perspectives for curitiba, Brazil *Energy Emiss. Control Technol.* **46** 621–34
- Krüger E L, Minella F O and Rasia F 2011 Impact of urban geometry on outdoor thermal comfort and air quality from field measurements in Curitiba, Brazil *Build. Environ.* **46** 621–34
- Krzyżanowski M, Kuna-Dibbert B and Schneider J 2005 *Health Effects of Transport-Related Air Pollution* (Copenhagen: WHO Regional Office Europe)
- Lemonsu A, Viguié V, Daniel M and Masson V 2015 Vulnerability to heat waves: impact of urban expansion scenarios on urban heat island and heat stress in Paris (France) *Urban Clim.* **14** 586–605
- Lemoy R and Caruso G 2018 Evidence for the homothetic scaling of urban forms *Environ. Plan. B* (<https://doi.org/10.1177/2399808318810532>)
- Li X, Kamarianakis Y, Ouyang Y II, Billie L T and Brazel A 2017 On the association between land system architecture and land surface temperatures: evidence from a desert metropolis—Phoenix, Arizona, USA *Landscape Urban Plan.* **163** 107–20
- Lin W, Yu T, Chang X, Wu W and Zhang Y 2015 Calculating cooling extents of green parks using remote sensing: method and test *Landscape Urban Plan.* **134** 66–75
- Lohrey S and Creutzig F 2016 A 'sustainability window' of urban form *Transp. Res. D* **45** 96–111 Special Issue on Climate Change and Transport
- Martínez J G, Boas I, Lenhart J and Mol A P J 2016 Revealing Curitiba's flawed sustainability: how discourse can prevent institutional change *Habitat Int.* **53** 350–9
- Miao S, Chen F, LeMone M A, Tewari M, Li Q and Wang Y 2009 An observational and modeling study of characteristics of urban heat island and boundary layer structures in Beijing *J. Appl. Meteorol. Climatol.* **48** 484–501
- Mindali O, Raveh A and Salomon I 2004 Urban density and energy consumption: a new look at old statistics *Transp. Res. A* **38** 143–62
- Mora C *et al* 2017 Global risk of deadly heat *Nat. Clim. Change* **7** 501
- Nangini C *et al* 2019 A global dataset of CO<sub>2</sub> emissions and ancillary data related to emissions for 343 cities *Sci. Data* **6** 180280
- Newman P and Kenworthy J 2006 Urban design to reduce automobile dependence *Opolis* **2** 35–52
- Newman P G and Kenworthy J R 1989 *Cities and Automobile Dependence: A Sourcebook* (Aldershot: Gower)
- Normile D 2016 China rethinks cities *Science* **352** 916–8
- Oke T R 1973 City size and the urban heat island *Atmos. Environ.* **7** 769–79
- Oke T R 1988 Street design and urban canopy layer climate *Energy Build.* **11** 103–13
- Peng S, Piao S, Ciais P, Friedlingstein P, Ottle C, Bréon F-M, Nan H, Zhou L and Myneni R B 2012 Surface urban heat island across 419 global big cities *Environ. Sci. Technol.* **46** 696–703
- Prihodko L and Goward S N 1997 Estimation of air temperature from remotely sensed surface observations *Remote Sens. Environ.* **60** 335–46
- Rabinovitch J 1992 Curitiba: towards sustainable urban development *Environ. Urbanization* **4** 62–73
- Rabinovitch J and Leitman J 1996 Urban planning in Curitiba *Sci. Am.* **274** 46–53
- Scott A A, Waugh D W and Zaitchik B F 2018 Reduced urban heat island intensity under warmer conditions *Environ. Res. Lett.* **13** 064003
- Seto K C *et al* 2014 Human settlements, infrastructure and spatial planning *Climate Change 2014: Mitigation of Climate Change. IPCC Working Group III Contribution to AR5* (Cambridge: Cambridge University Press)
- Small K A, Verhoef E T and Lindsey R 2007 *The Economics of Urban Transportation* (London: Routledge)



- Spronken-Smith R A and Oke T R 1998 The thermal regime of urban parks in two cities with different summer climates *Int. J. Remote Sens.* **19** 2085–104
- Stevens M R 2017 Does compact development make people drive less? *J. Am. Plan. Assoc.* **83** 7–18
- Stewart I D and Oke T R 2012 Local climate zones for urban temperature studies *Bull. Am. Meteorol. Soc.* **93** 1879–900
- Streutker D R 2002 A remote sensing study of the urban heat island of Houston, Texas *Int. J. Remote Sens.* **23** 2595–608
- Susca T, Gaffin S R and Dell'Oso G R 2011 Positive effects of vegetation: urban heat island and green roofs *Environ. Pollut.* **159** 2119–26
- United Nations 2014 *World Urbanization Prospects: The 2014 Revision, Highlights* ST/ESA/SER.A/352 United Nations, Department of Economic and Social Affairs, Population Division.
- Wang J, Huang B, Fu D, Atkinson P M and Zhang X 2016 Response of urban heat island to future urban expansion over the Beijing–Tianjin–Hebei metropolitan area *Appl. Geogr.* **70** 26–36
- Wang J, Yan Z, Quan X-W and Feng J 2017 Urban warming in the 2013 summer heat wave in eastern China *Clim. Dyn.* **48** 3015–33
- Ward K, Lauf S, Kleinschmit B and Endlicher W 2016 Heat waves and urban heat islands in europe: a review of relevant drivers *Sci. Total Environ.* **569** 527–39
- Westman L and Broto V C 2018 Climate governance through partnerships: a study of 150 urban initiatives in China *Glob. Environ. Change* **50** 212–21
- Xu L, Cui S, Tang J, Nguyen M, Liu J and Zhao Y 2019 Assessing the adaptive capacity of urban form to climate stress: a case study on an urban heat island *Environ. Res. Lett.* **14** 044013
- Zhou B, Rybski D and Kropp J P 2013 On the statistics of urban heat island intensity *Geophys. Res. Lett.* **40** 5486–91
- Zhou B, Rybski D and Kropp J P 2017 The role of city size and urban form in the surface urban heat island *Sci. Rep.* **7** 4791
- Zhou D, Zhao S, Zhang L, Sun G and Liu Y 2015 The footprint of urban heat island effect in China *Sci. Rep.* **5** 11160