nature portfolio

Peer Review File

Big-Data Empowered Traffic Signal Control Could Reduce Urban Carbon Emissions

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This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
This paper is not convincing as a piece of communication. For it to be credible and impactful, it needs to be submitted to a reputable, peer-reviewed regular journal. This way, both the methodology and the case study presented in the paper will merit thorough and detailed explanations. This includes providing comprehensive descriptions of the research design, data collection, and analysis processes, as well as an in-depth discussion of the case study's context, findings, and implications. Only with this level of detail can the paper effectively persuade its audience of its validity and significance.

(Remarks on code availability)
N/A

Reviewer #2

(Remarks to the Author)
This paper presents the potential of traffic signal control using big data on reducing urban carbon emission for 100 Chinese cities. The topic is interesting and the paper is easy to read. However, I question the novelty of the methods and the importance of results to be sufficient for publishing this manuscript in Nature Communications. Let me elaborate my points as follows.

Using adaptive traffic signals to alleviate congestion should be the primary innovative point of this study. However, the current version does not sufficiently demonstrate the progress made in this aspect.
• There are many studies on using adaptive traffic light systems to control traffic congestion, but the authors have not adequately introduced the advancements in this field in the Introduction. Furthermore, in the last paragraph, the author merely state, "we first demonstrated how adaptive traffic signals can alleviate congestion at both isolated intersections and city-wide levels." At this point, it may lead readers to believe that this paper merely applies an existing adaptive traffic signals algorithm to intersections in different cities, which, while heavy workload, lacks innovation.
• In the first section of the Results, the authors mention "our proposed adaptive method," suggesting that the authors have proposed an innovative algorithm. However, the presented results are not satisfied. After introducing how the adaptive method can reduce congestion, the authors should first compare the proposed adaptive method with other research methods in terms of alleviating congestion to demonstrate the advantages of their method. Currently, the comparison is only with the BAU scenario, which is unconvincing, as it is entirely predictable that sampling adaptive traffic light systems can alleviate congestion.

The current version does not highlight the importance and significance of using traffic signal control to reduce urban carbon emissions, making it seem like a forced combination of two different works (smart traffic and emission calculation).
• In the Introduction, the author discusses the contribution of the transport sector to carbon emissions and mention that the increase in future vehicle population will exacerbate urban traffic congestion. However, the author does not introduce the contribution of traffic congestion to carbon emissions. Thus, it is unclear whether solving traffic congestion is a key step in mitigating future transport carbon emissions, which undermines the importance of this work.
• In the third section of the Results, it is stated that total CO_2 emissions could be reduced by 40 Mt (a 6% reduction) each year. This reduction seems very small, further making me feel that this work might not be that important. Whether in terms of emission reduction or cost-benefit, I cannot simply infer from these numbers whether the benefits of this measure are

sufficiently positive. In other words, the authors should try to compare these benefits with existing or future possible vehicle emission control policies (e.g., odd-even license plate restrictions, emission standard upgrades, electrification) to demonstrate the value of reducing carbon emissions by alleviating traffic congestion.

• Furthermore, the current benefit analysis should be overestimated. First, the baseline transport CO2 emission data is from 2015, but in recent years, a series of emission control policies have been implemented, and vehicle emissions have decreased. Therefore, analyzing based on the relatively high vehicle emissions in 2015 seems inappropriate. Second, the authors mentioned in the Introduction that some cities have already adopted adaptive traffic light systems. However, in the BAU scenario, all traffic signals in a city's downtown area were pretimed. The BAU scenario setting is too idealized and does not reflect the actual situation, leading to an overestimation of the results。

Other comments:

• Line 402, Emission model: This formula should be not solid. CO2 emissions are related to engine displacement and vehicle weight, and the response of emissions from different vehicle types to speed is still uncertain. Regulatory tests only constrain the overall conditions and do not directly establish a relationship between average speed and emissions. To make the conclusions of the entire paper valid, this relationship must first be proven reliable. However, this relationship is only from a model published in 2008.

• The Results and Discussion sections are not well-written, primarily describing the data on the figures without further explanation and discussion, making it look like a report.

• I am unsure whether calculating the benefit-cost ratio is appropriate because not all costs and benefits are considered. Adding new costs or benefits may change the qualitative conclusions.

• The content of Policy Implications does not seem to be related to the Results. In other words, it seems like the current Policy Implications could also be written without the results conducted in this paper.

• GHSL-UCDB (mentioned in Line 398) should be defined in Line 271.

(Remarks on code availability)

Reviewer #3

(Remarks to the Author)

I co-reviewed this manuscript with one of the reviewers who provided the listed reports. This is part of the Nature Communications initiative to facilitate training in peer review and to provide appropriate recognition for Early Career Researchers who co-review manuscripts

(Remarks on code availability)

Reviewer #4

(Remarks to the Author)

The paper explores the impact of implementing adaptive traffic signal control systems in reducing urban congestion and carbon emissions. The study focuses on the top 100 most congested cities in China, using data from OpenStreetMap and Gaode Map for road network and travel speed data.

The authors propose an adaptive signal control method that leverages real-time traffic data to optimize traffic flow and reduce emissions. The paper includes simulated experiments to demonstrate the potential benefits of this approach, such as significant reductions in trip times, fuel consumption, and CO2 emissions.

The work is significant as it addresses a pressing issue in urban planning and transportation engineering by providing a scalable and cost-effective solution to traffic congestion.

The proposed method builds on previous studies, such as extending works on adaptive traffic signal control using dynamic programming and real-time systems like City Brain and also includes a benefit-cost analysis.

The methodology is sound and meets the expected standards. The use of simulation-based experiments demonstrates a rigorous approach.

The benefit-cost ratios and the detailed regression analysis between speed improvement and city indicators validate the effectiveness of the proposed method.

The paper provides sufficient details for replication by including a description of data sources, experiment setup, and the adaptive signal control algorithm. In addition, the description of the simulation environment and the steps taken to generate synthetic trips ensures that other researchers can reproduce the study's findings with similar datasets.

(Remarks on code availability)

The introduction highlights the challenges of urban congestion and its impact on carbon emissions.

The use of OpenStreetMap and Gaode Map data for simulations is well-explained. Further details on the data preprocessing steps and the criteria for selecting the 100 most congested cities would enhance the transparency of the methodology. Also, including a flowchart or diagram of the adaptive signal control method could help readers visualize the process.

The results show significant reductions in trip times and emissions. It might be nice to consider discussing the potential variability in these results across different urban settings and traffic conditions.
The multivariate linear regression analysis offers valuable insights into the factors influencing congestion mitigation potential.

The cost-benefit analysis is a strong aspect of the paper AND is particularly useful for policymakers. Providing examples of cities with different ratios and discussing the implications for urban planning could add practical value.

The figures and tables are well-designed and effective.
The manuscript is well-organized and clearly written.
Data and code are available on github.

Additional references suggested:

Lertworawanich P., Unhasut P., A CO emission-based adaptive signal control for isolated intersections, Journal of the Air and Waste Management Association, 2021, 71 (5), pp. 564 - 585, DOI: 10.1080/10962247.2020.1862940

Li X., Li G., Pang S.-S., Yang X., Tian J.,Signal timing of intersections using integrated optimization of traffic quality, emissions and fuel consumption: A note, Transportation Research Part D: Transport and Environment, 9 (5), 2004, pp. 401 - 407, DOI: 10.1016/j.trd.2004.05.001

Chiara Bachechi, Laura Po, Federica Rollo, Big Data Analytics and Visualization in Traffic Monitoring, Big Data Research, Volume 27, 2022, 100292, ISSN 2214-5796,
https://doi.org/10.1016/j.bdr.2021.100292.

Version 1:

Reviewer comments:

Reviewer #2

(Remarks to the Author)
The authors have addressed all my comments very well. I do not have further question.

(Remarks on code availability)

Reviewer #3

(Remarks to the Author)
I co-reviewed this manuscript with one of the reviewers who provided the listed reports. This is part of the Nature Communications initiative to facilitate training in peer review and to provide appropriate recognition for Early Career Researchers who co-review manuscripts.

(Remarks on code availability)

Response to referees

Referee #2

Comment		**Response** and **Change**
R2-1	**Major Comments:** This paper presents the potential of traffic signal control using big data on reducing urban carbon emission for 100 Chinese cities. The topic is interesting and the paper is easy to read. However, I question the novelty of the methods and the importance of results to be sufficient for publishing this manuscript in Nature Communications. Let me elaborate my points as follows.	We sincerely appreciate your detailed review and insightful feedback, which has been instrumental in helping us critically re-evaluate and strengthen our manuscript. 1. In line with your suggestions, we have clearly articulated our research contributions and key innovations in the revised Introduction section. 2. To enhance the robustness of our findings, we updated the emission datasets, refined our transportation emissions estimation model and re-ran all simulation experiments accordingly. 3. We also revised the cost-benefit analysis and replace the previous “Policy implication” section with a new “Discussion” section. These updates highlight how our research advances the field and suggest how our findings may support policy shifts to leverage big data for targeted emissions reductions in transportation and other urban sectors. Thank you for helping us improve the quality of this manuscript. The major revisions are detailed in our responses to the following comments.
R2-2	Using adaptive traffic signals to alleviate congestion should be the primary innovative point of this study. However, the current version does not sufficiently demonstrate the progress made in this aspect. There are many studies on using adaptive traffic light systems to control traffic congestion, but the authors have not adequately introduced the advancements in this field in the Introduction. Furthermore, in the last paragraph,	Thank you for your thorough review and insightful comments. **First,** our study proposes a comprehensive framework to evaluate the system-wide impacts of big-data-enabled adaptive traffic signals on reducing congestion and emissions across Chinese megacities, rather than merely developing a new adaptive traffic signal algorithm. Our focus is not on comparing various new traffic signal algorithms, but rather on evaluating the effectiveness of these methods for managing traffic in major cities facing severe congestion from a systematic perspective. Implementing such solutions can also support goals for carbon neutrality and urban sustainability, pressing needs in modern urban planning to which the transportation sector can make a significant contribution. While other adaptive traffic signal algorithms may also drive this transformation, our paper specifically addresses big-data-enabled adaptive traffic signals, as this approach has been recently proposed and demonstrated by the Chinese government. We believe our study can support a potential policy shift toward using big data for targeted emissions reductions in

	the author merely state, "we first demonstrated how adaptive traffic signals can alleviate congestion at both isolated intersections and city-wide levels." At this point, it may lead readers to believe that this paper merely applies an existing adaptive traffic signals algorithm to intersections in different cities, which, while heavy workload, lacks innovation. In the first section of the Results, the authors mention "our proposed adaptive method," suggesting that the authors have proposed an innovative algorithm. However, the presented results are not satisfied. After introducing how the adaptive method can reduce congestion, the authors should first compare the proposed adaptive method with other research methods in terms of alleviating congestion to demonstrate the advantages of their method. Currently, the comparison is only with the BAU scenario, which is unconvincing, as it is entirely predictable that sampling adaptive traffic light systems can alleviate congestion.	urban mobility, especially for cities currently focused only on congestion reduction. **Second,** we recognize that adaptive signal control has advanced significantly, from heuristic approaches to data-intensive reinforcement learning. However, deployment in China is still limited due to high demands for data quality, real-time access, and processing costs. Our study addresses this by emphasizing the need for adaptive methods that balance responsiveness with resilience to data limitations. In this context, simpler cycle-based methods, such as Webster's, are widely adopted due to their lower data requirements and effective integration with smart city platforms like City Brain, making them particularly suited to China's high-density urban environments. In response, we have expanded the "Introduction" section to further review the evolution of adaptive signal control and highlight our main research contributions. The corresponding revisions are listed below. **Introduction (Line 63-95) :** "Research on adaptive traffic signal control has progressed over decades, evolving from early heuristic methods to data-intensive reinforcement learning approaches[15,16]. Adaptive control methods fall into two primary categories: cycle-based methods (e.g., Webster's algorithm[17–19], SCATS and SCOOT[20,21]) and phase-based methods (e.g., max-pressure[22–24] and reinforcement learning algorithms[25–27]). Cycle-based methods, which maintain consistent phase settings, are widely used because they require less data and provide straightforward rules for drivers to follow. Phase-based methods, which adjust phases in real time, offer greater adaptability but face challenges in Chinese cities where timely, high-quality data are often limited, and local driving and pedestrian behaviors require careful consideration. Although multi-source traffic data is now available, collecting and processing this data remains costly and can sometimes be unreliable. Therefore, signal timing update methods that are less data-dependent and more robust to data errors are still essential. **In this context, it is not the novelty of traffic control algorithms but rather their compatibility with available data that becomes crucial. Consequently, simpler cycle-based algorithms like Webster's method have gained traction in China, particularly when integrated with platforms such as City Brain**[28,29]. Pilot projects in Hangzhou and Nanchang have shown over 15% reductions in trip delays[30], demonstrating adaptive traffic signal control's potential in lifting long-standing traffic restrictions without increasing congestion. While pilot projects and extensive research on isolated intersections[31,32] show promise, systematic studies on the city-wide impacts of adaptive traffic signals - particularly considering both

		congestion and emissions reduction - are still limited. We address this research gap by conducting simulated experiments on China's 100 most congested cities, using OpenStreetMap[33] for road network data and Gaode Map for travel speed data. Our analysis quantifies congestion and emission reductions at both isolated intersections and city-wide levels, identifies key socioeconomic and infrastructure factors influencing congestion mitigation potential, and assesses the cost-effectiveness of adaptive traffic signal systems. **To our knowledge, this study is the first to evaluate the large-scale implementation of big-data-driven adaptive traffic signals in megacities, specifically focusing on urban areas with populations exceeding 10 million and thousands of signalized intersections. Through this comprehensive examination of city-scale adaptive traffic signals, our study advances the understanding of big-data empowered traffic management and offers insights for developing low-emission, efficient urban mobility solutions aligned with China's sustainability targets. "**
R2-3	The current version does not highlight the importance and significance of using traffic signal control to reduce urban carbon emissions, making it seem like a forced combination of two different works (smart traffic and emission calculation).	Thank you for your insightful comments. We agree that the significance of big-data-empowered traffic signals for reducing urban carbon emissions should be more clearly emphasized in our work. **From a theoretical perspective,** in dense urban environments like Chinese cities, traffic congestion at intersections causes frequent braking and idling, leading to significant additional emissions. As traffic volumes rise, addressing these emissions is crucial for urban carbon reduction. Adaptive traffic signals help reduce emissions by minimizing braking and idling times at intersections, smoothing traffic flow, and improving vehicle efficiency. This approach not only alleviates congestion but also directly mitigates emissions, positioning adaptive signal control as a highly relevant strategy for low-carbon urban transport. **From a practical perspective,** we conducted a simulation experiment covering 17.37 km with 20 signalized intersections in Shanghai to illustrate these benefits. Using the Motor Vehicle Emission Simulator (MOVES) model, we assessed the impact of adaptive signals on driving patterns and CO_2 emissions. Results showed adaptive control reduced idling from 13 to 6.78 minutes and braking time from 16.47 to 14.72 minutes, nearly halving idle time. These adjustments in driving behavior led to a 16% reduction in CO_2 emissions, or 0.8 kg, underscoring adaptive signals' emission-reducing potential in congested urban areas. To address this more explicitly, we have strengthened the discussion on the role of traffic congestion in emissions generation in the "Results" section. The corresponding revisions are listed below.

		Results – How adaptive traffic signal mitigates urban congestion? (Line 111-136): "Adaptive traffic signals also contribute to emissions reduction by minimizing vehicle stops and idling time. In densely populated Chinese cities, the frequent proximity of intersections - averaging about 500 meters apart in urban centers - means that vehicles encounter multiple stops during typical trips. Furthermore, the complexity of urban traffic, including interactions with pedestrians and cyclists, often leads to additional braking and idling at intersections, exacerbating emissions and reducing traffic efficiency. This study directly compares pre-timed and adaptive traffic signals in terms of their ability to smooth traffic flow and reduce emission, controlling for signal timing by applying Webster's method to both. The key distinction lies in data input: pre-timed traffic signals rely on static historical data, while adaptive traffic signals use real-time data to dynamically adjust green times. This dynamic adjustment reduces vehicle stops and decelerations, thereby lowering congestion and emissions. To quantify these advantages, we conducted a demonstration trip spanning 17.37 km and 20 signalized intersections in Shanghai. Using the Motor Vehicle Emission Simulator (MOVES) model[34], we assessed adaptive traffic signals' impact on driving patterns and CO_2 emissions. Adaptive control significantly decreased braking and idling times (Extended Data Table 1), reducing idling time from 13 minutes to 6.78 minutes and braking time from 16.47 to 14.72 minutes, effectively halving idling duration. This reduction, coupled with an increase in cruising time under low- or medium-speed conditions, raised average travel speed by 17% and reduced trip duration by 7 minutes. These improvements in driving patterns yielded notable emissions reductions. Along the demonstration trip, CO_2 emissions fell from 4.85 kg to 4.05 kg, driven by the reduction in braking and idling. Overall, adaptive traffic signals achieved a net CO_2 reduction of 16% (Fig. 2b), demonstrating that optimized signal timing not only improves traffic flow but also mitigates emissions by reducing braking and idling time at intersections."

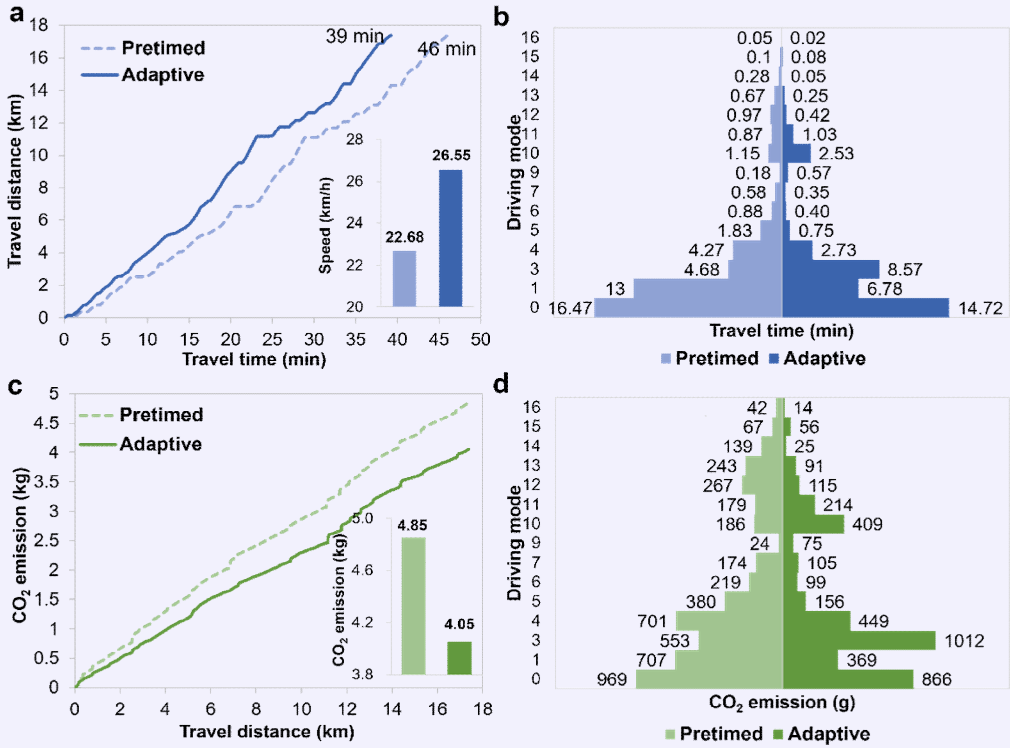
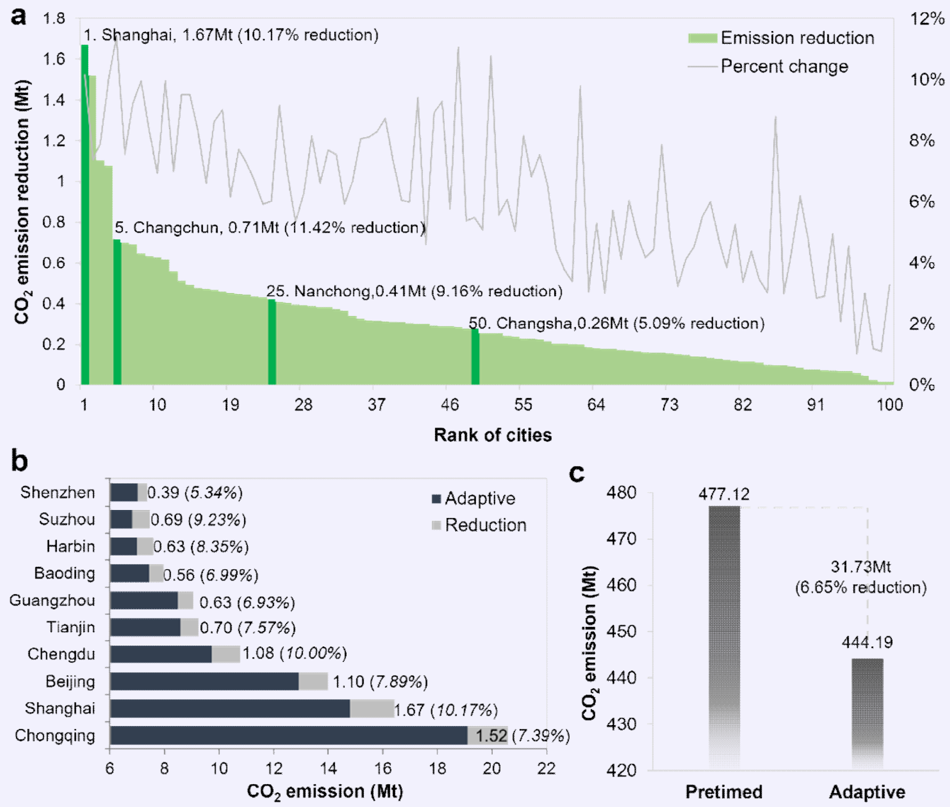
<table>
<tr><td></td><td></td><td>

Fig. 2 | Impact of adaptive traffic signals on vehicle's travel speed, driving modes, and CO_2 emissions. a, In Shanghai, the demo vehicle's travel speed increased from 22.68 to 26.55 km/h with adaptive traffic signals. **b,** Comparison of durations in various driving modes for the demo trip: adaptive signals reduce time spent in braking (mode-0) and idling (mode-1) at intersections, with a significant increase in cruising time (mode-3 and mode-10). **c,** CO_2 emissions decreased from 4.85 kg to 4.05 kg during the demo trip (16% reduction). **d,** Comparison of CO_2 emissions across driving modes shows that emission savings from reduced braking and idling outweigh the increase during cruising, resulting in a net 16% emission reduction. Refer to Extended Data Table 1 for detailed driving mode definitions.</td></tr>
<tr><td>R2-4</td><td>In the Introduction, the author discusses the contribution of the transport sector to carbon emissions and mention that the increase in</td><td>Thank you for pointing out this critical issue. We fully agree that the contribution of urban congestion to carbon emissions needs to be more explicitly introduced to underscore the significance of addressing congestion as a key step in mitigating future transport-related emissions.</td></tr>
</table>

	future vehicle population will exacerbate urban traffic congestion. However, the author does not introduce the contribution of traffic congestion to carbon emissions. Thus, it is unclear whether solving traffic congestion is a key step in mitigating future transport carbon emissions, which undermines the importance of this work.	Upon reviewing multiple sources, we found that in European cities, the contribution of urban congestion to carbon emissions varies between 7% and 15%, while in major cities in China, this contribution ranges from 12.7% to 14.2%. These rough estimates underscore the substantial role congestion plays in driving emissions in urban environments. For example, in London, congestion alone contributes approximately 2.2 million tonnes (Mt) of CO_2 annually, accounting for 15% of total road traffic emissions. This amount is equivalent to the carbon sequestration potential of a pine forest the size of Sydney (12,000 km^2). This illustrates that mitigating congestion is critical for achieving urban decarbonization targets, particularly in rapidly growing cities like those in China. Following your suggestions, the corresponding revisions are listed below. **Introduction (Line 31-46):** "Road traffic is a major global source of carbon emissions, generating approximately 5.88 billion tonnes of greenhouse gas (GHG) annually (measured in CO_2-equivalent), or 11.9% of total emissions, ranking third among all sectors (Extended Data Fig. 1a)[1]. Urban congestion further exacerbates these emissions. In cities like London, congestion alone contributes around 2.2 million tonnes (Mt) of CO_2 annually, equating to 15% of total road traffic emissions, which would require a pine forest the size of Sydney (12,000 km^2) to offset[2]. Similar congestion impacts are observed in Paris (2.8 Mt, 13%), Berlin (0.42 Mt, 10.5%), and Amsterdam (0.06 Mt, 7%)[2]. The situation is particularly acute in rapidly growing megacities in China, where congestion-related emissions are amplified by high traffic demand and infrastructure constraints. In China, transport emissions surged from 96 Mt in 1990 to 996 Mt in 2021 - a compound annual growth rate of 7.83% driven by urbanization and economic growth (Extended Data Fig. 1b)[3]. For cities like Suzhou, Chengdu, and Harbin, reducing congestion could potentially cut emissions by 0.95 (12.7%), 1.53 (14.2%), and 0.98 Mt (12.9%) of CO_2, respectively[4]. This rise in urban traffic emissions poses a challenge to China's 2060 carbon neutrality target[5] and threatens progress on sustainable development goals (SDGs) related to sustainable cities, infrastructure, and climate action[6]."
R2-5	In the third section of the Results, it is stated that total CO_2 emissions could be reduced by 40 Mt (a 6% reduction) each year. This reduction seems very small, further making me feel that this work	Thank you for this valuable suggestion. We agree that comparing emissions reductions from adaptive traffic signals with other strategies will make the results more intuitive for readers. To address this, we re-evaluated the potential CO_2 emissions reduction using the Motor Vehicle Emission Simulator (MOVES), a comprehensive model by the United States Environmental Protection Agency, along with updated business-as-usual (BAU) emissions data from the Climate

	might not be that important. Whether in terms of emission reduction or cost-benefit, I cannot simply infer from these numbers whether the benefits of this measure are sufficiently positive. In other words, the authors should try to compare these benefits with existing or future possible vehicle emission control policies (e.g., odd-even license plate restrictions, emission standard upgrades, electrification) to demonstrate the value of reducing carbon emissions by alleviating traffic congestion.	Watch Database (2021). Our findings indicate that adaptive traffic signals could reduce annual CO_2 emissions by 31.73 Mt (a 6.65% reduction) across 100 cities. To make these numbers comparable, this emissions offset is equivalent to replacing 9.16 million (approximately 3.3%) petrol vehicles with electric vehicles each year in China. This provides a more concrete sense of scale for the emissions benefits derived from adaptive traffic signals alone. Additionally, adaptive traffic signals can complement existing policies (e.g., odd-even restrictions, emission standard upgrades, and electrification) for a greater combined impact. Our paper discusses these synergies within the "Avoid-Shift-Improve" framework in the "Discussion" sections. Future research could build on this by examining combined strategies, such as integrating adaptive traffic signals with dynamic lanes, green wave coordination, and the 15-minute city concept. Following your suggestions, the corresponding revisions are listed below. **Results - Reduction of carbon emission (Line 192-211):** "The annual road traffic CO_2 emissions across the 100 cities were approximately 477 Mt in 2021, according to the Climate Watch Database[3]. Our analysis reveals that implementing adaptive traffic signals could reduce CO_2 emissions by 31.73 Mt annually - a 6.65% reduction across these cities (Fig. 4c). **This reduction is equivalent to the offset that would be achieved by replacing 9.16 million petrol vehicles (3.30% of all private vehicles) with electric ones each year in China (see *Methods*).** The CO_2 reduction potential varied significantly by city, from 16 Kt in Sanya to 1.67 Mt in Shanghai (Fig. 4a), with the top 10 cities accounting for nearly 30% of the total emission reductions, while the bottom 10 cities contributed only 1.64%. Even lower-ranked cities, such as Changsha, which saw a 5.09% reduction, showed meaningful potential for emission reduction when considering percentage improvements in urban air quality and health outcomes. Transport emissions reductions are influenced by both baseline emissions and the impact of adaptive traffic signals. In 2021, baseline BAU CO_2 emissions across the cities ranged widely, from 0.5 Mt in Sanya to 20.6 Mt in Chongqing. In general, cities with higher BAU emissions show greater absolute reduction potential; however, reductions are not directly proportional to BAU emissions. For example, despite Shanghai's lower BAU emissions than Chongqing (Fig. 4b), Shanghai's reduction potential was higher (1.67 Mt vs. 1.52 Mt). This underscores the importance for cities to evaluate their specific reduction potential prior to implementation, as city-specific characteristics can significantly affect outcomes."

		Discussion (Line 321-330): "With road transport contributing 11.9% of global CO_2 emissions and ranking among the top three emitting sectors worldwide (Extended Data Fig. 1), data-driven congestion mitigation solutions offer significant potential for supporting China's carbon neutrality and sustainable development goals (SDGs). **Future research could expand on our framework by examining the emission reduction potential of integrated "Avoid-Shift-Improve" solutions.** For instance, further studies could explore "Improve" measures like big-data empowered dynamic variable lanes and green wave coordination, "Shift" strategies such as transit-oriented development, and "Avoid" approaches like the 15-minute city concept. Our framework and models provide a foundation for assessing city-wide congestion and emissions reduction strategies, aligning with broader efforts toward urban sustainability." **Methods - Transport emission (Line 515-522):** "To estimate the number and proportion of petrol vehicles that need to be replaced by electric vehicles, we first use data from *Our World in Data*[52] to calculate the difference in CO_2 emissions per passenger-kilometer between petrol and electric vehicles. Next, we apply the annual average mileage of vehicles in China[53] to determine the annual emissions reduction when a vehicle is replaced by an electric engine. Finally, we divide the total emissions reduction achieved through adaptive signals by this annual per-vehicle reduction to estimate the number of vehicles that need to be replaced each year. The percentage is then calculated by comparing this figure with the total number of privately owned vehicles in China in 2022[54]."

		 **Fig. 4 | Reduction of CO_2 emission. a**, Histogram of annual CO_2 reductions with percentage changes indicated by a broken line, labeled for typical cities. **b**, Ranking of the top 10 cities by BAU annual CO_2 emissions: dark bars represent predicted total emissions, while light bars show potential reductions under adaptive traffic signals, labeled are emission reduction and percent change. **c**, Annual transport CO_2 emission reductions across 100 cities.
R2-6	Furthermore, the current benefit analysis should be overestimated. First, the baseline transport CO_2 emission data is from 2015, but in recent years, a series of emission control policies have been	Thank you for highlighting these critical points, which have helped us improve the robustness of our analysis. We have addressed each of your concerns as follows: 1. **Updated emissions data:** We have updated our business-as-usual (BAU) emissions baseline using the most recent 2021 data from the Climate Watch Database for China. While the 2021 dataset reflects more current vehicle emissions and reduces the risk of overestimation, it is also

	implemented, and vehicle emissions have decreased. Therefore, analyzing based on the relatively high vehicle emissions in 2015 seems inappropriate. Second, the authors mentioned in the Introduction that some cities have already adopted adaptive traffic light systems. However, in the BAU scenario, all traffic signals in a city's downtown area were pretimed. The BAU scenario setting is too idealized and does not reflect the actual situation, leading to an overestimation of the results.	widely cited and recognized as highly reliable for emissions studies, ensuring consistency in our comparative analysis. 2. **Clarification on adjustments for existing adaptive signals in cities:** In the previous version, we have excluded pilot adaptive traffic signals in cities like Hangzhou and Nanchang, designating the corresponding intersections as adaptive instead of pre-timed. We apologize for not stating this important information in the previous version. In this revision, we also conducted a thorough review of other urban centers to confirm the absence of extensive adaptive signal implementations in their downtown areas, refining our BAU scenario to better reflect real-world conditions. 3. Regarding the response to concerns about overestimating our results, please refer to the details provided later in "**R2-9**". The corresponding revisions are listed below. **Results - Congestion mitigation potential across China (Line 151-165):** "Our results show that the potential for congestion mitigation is universal and not limited to a few mega-cities, by using data from the top 100 congested cities in China ranked by Gaode in 2022. By altering all traffic signals in each city from pre-timed to adaptive, we found that 97 of the 100 cities could expect a non-trivial change in average speed (greater than 1%), with 49 cities expecting an increase of more than 10% during peak hours. Trip time would be reduced by 11% (79,695 hours) during peak hours across all 100 cities. During off-peak hours, trip time reduction was about 8% (42,080 hours) (Extended Data Fig 3). **For cities like Hangzhou and Nanchang, which have previously reported the integration of big data to enhance signal adaptivity, our baseline BAU scenario accounted for their existing adaptive traffic signals.** Geographically, we found that cities with high mitigation potential were mainly coastal or provincial capitals, which are important for economic development in China (Fig. 3a-c). We ranked 100 cities based on reductions in trip time and found that Shanghai, Beijing, Harbin, Qingdao, and Shenzhen were the top 5 cities. Shanghai alone could save up to 6,581 hours (an 18% reduction) in total trip time during peak hours. This reduction is significant, as each trip could save up to 9 minutes on average (Fig. 3d)." **Methods - Transport emission (Line 468-473): "The baseline transport emissions data were derived from the Climate Watch Database, which reported China's total transport-related emissions as 996.35 million tonnes (Mt) in 2021.** Given that road transport contributes approximately 73.46% to global transport emissions, China's road transport emissions were

		estimated to be 731.89 Mt annually. To estimate city-specific emissions, we apportioned this total according to urban population size, assuming that per capita emissions within cities align with national averages.”
R2-7	Other comments: Line 402, Emission model: This formula should be not solid. CO_2 emissions are related to engine displacement and vehicle weight, and the response of emissions from different vehicle types to speed is still uncertain. Regulatory tests only constrain the overall conditions and do not directly establish a relationship between average speed and emissions. To make the conclusions of the entire paper valid, this relationship must first be proven reliable. However, this relationship is only from a model published in 2008.	Thank you for highlighting this critical issue. We agree that early speed-based emission models may lack the precision needed for accurate CO_2 emissions modeling. To address this, we adopted the latest version of the Motor Vehicle Emission Simulator (MOVES), MOVES4 (released by the U.S. Environmental Protection Agency in 2023), which provides a more robust and scientifically validated framework for emissions estimation. MOVES4's extensive validation and application in both research and regulatory contexts underscore its reliability, making it a solid foundation for the conclusions in our study. The corresponding revisions are listed below. **Methods - Transport emission (Line 475-507):** “To evaluate the impact of adaptive traffic signals on transport emissions, we utilized the Motor Vehicle Emission Simulator (MOVES), an on-road emission model developed by the United States Environmental Protection Agency. The MOVES model is recognized for its application in research and policy[49–51] due to its vehicle-specific power (VSP) framework, which enables detailed emission analyses. In this framework, VSP is calculated for each vehicle at a microscopic level based on instantaneous speed, acceleration, road grade, and road load coefficient. The VSP is computed using the following equation: $$VSP = \frac{A \cdot v_t + B \cdot v_t^2 + C \cdot v_t^3 + m \cdot v_t \cdot a_t}{m}$$ where v_t is vehicle’s speed at time t (m/s), a_t is vehicle’s acceleration at time t (m/s^2), and m denotes vehicle mass (tonnes); A, B, C correspond to coefficients of rolling resistance, rotational resistance, and aerodynamic drag, respectively, and vary by vehicle type. For example, for a passenger 39 car, $A = 0.1565, B = 2.002 \times 10^{-3}, C = 4.926 \times 10^{-4}$, and $m = 1.479$ tonne. Although road grade is also a factor in VSP, default MOVES assume zero grade. Using vehicle trajectory data from CBEngine, we classified vehicle driving modes based on instantaneous speed and calculated VSP values. Emissions for each vehicle were quantified according to emission factors specific to each driving mode (see Extended Data Fig. 1). The total

		emissions (TE) across all vehicle trips were calculated as follows: $$E_{i,t} = f_i(VSP_t, v_t)$$ $$TE = \sum_i \sum_t E_{i,t}$$ where $E_{i,t}$ represents the emissions of vehicle i during time period t. Adaptive traffic signals influence vehicle driving modes by minimizing idle and braking times at intersections, which the MOVES model accounts for, enabling us to estimate CO_2 emission reductions attributable to these adaptive traffic signals. Adaptive traffic signals can influence vehicle driving modes by reducing idle time and minimizing braking at intersections. By comparing emissions data under pre-timed and adaptive traffic signal conditions, we assessed the reduction in CO_2 emissions attributable to adaptive traffic signals. Using MOVES, we estimated the average emissions change per vehicle due to adaptive signaling and scaled this difference to represent city-level changes, accounting for the city's population size. This approach allowed us to estimate the total CO_2 emissions reduction achievable through city-wide implementation of adaptive traffic signals." **Extended Data Table 1 | Average emission rates by driving mode for passenger cars (gasoline) in the MOVES model.**

Dring mode	Driving mode definition		CO_2 emission (g/min)
0	Braking		58.8
1	Idling		54.4
2	VSP < 0		85.6
3	0 ≤ VSP < 3		118.2
4	3 ≤ VSP < 6	1.6 ≤ Speed < 40	164.2
5	6 ≤ VSP < 9		207.5
6	9 ≤ VSP <12		247.4
7	12 ≤ VSP		298.8
8	VSP < 0		116.4
9	0 ≤ VSP < 3		132.5
10	3 ≤ VSP < 6		161.4
11	6 ≤ VSP < 9	40 ≤ Speed < 80	207.1
12	9 ≤ VSP < 12		276.3

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<tr><td>13</td><td>12 ≤ VSP < 18</td><td></td><td>364.3</td></tr>
<tr><td>14</td><td>18 ≤ VSP < 24</td><td></td><td>491.0</td></tr>
<tr><td>15</td><td>24 ≤ VSP < 30</td><td></td><td>672.7</td></tr>
<tr><td>16</td><td>30 ≤ VSP</td><td></td><td>844.7</td></tr>
<tr><td>17</td><td>VSP < 6</td><td rowspan="6">80 ≤ Speed</td><td>165.9</td></tr>
<tr><td>18</td><td>6 ≤ VSP < 12</td><td>265.9</td></tr>
<tr><td>19</td><td>12 ≤ VSP < 18</td><td>346.4</td></tr>
<tr><td>20</td><td>18 ≤ VSP < 24</td><td>451.7</td></tr>
<tr><td>21</td><td>24 ≤ VSP < 30</td><td>601.7</td></tr>
<tr><td>22</td><td>30 ≤VSP</td><td>767.0</td></tr>
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<td>R2-8</td>
<td>The Results and Discussion sections are not well-written, primarily describing the data on the figures without further explanation and discussion, making it look like a report.</td>
<td>Thank you for your valuable suggestions. We have significantly revised the “Results” and “Discussion” sections to enhance clarity and depth. Below are the major improvements we made:

1. How adaptive traffic signal mitigates urban congestion: To provide a clearer understanding of how adaptive traffic signals reduce congestion, we included a demonstration trip covering 17.37 km and 20 intersections in Shanghai. This example illustrates how adaptive traffic signals can effectively reduce congestion and emissions, grounding the results in a real-world context.
2. Reduction of carbon emission: To make our findings more accessible and relatable, we compared the emissions reductions achieved through adaptive traffic signals with replacing petrol vehicles with electric ones. As a result, the reduction is equivalent to replacing approximately 9.16 million (or 3.3% of all private vehicles) of petrol vehicles with electric vehicles annually in China, offering readers a concrete sense of the scale of impact.
3. Cost and benefit: For implementation costs, we discuss the potential for data processing costs to decrease with centralized smart city systems, which facilitate cross-sector data-sharing. On the benefits side, we emphasize the broader environmental and societal advantages associated with adaptive traffic signals, which could influence city-wide decision-making on adaptive traffic signal implementation.
4. Discussion: We have renamed the “Policy Implications” section as “Discussion” and restructured it to provide a summary of the main findings, address study limitations, and suggest future research directions. The discussion now also considers the potential of big data and other approaches to mitigate urban transport emissions within the “Avoid-Shift-Improve” framework, connecting our work to the broader scientific discourse on congestion and emissions reduction.</td>
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		We believe these changes create a more thorough and insightful analysis, moving beyond descriptive reporting to provide meaningful interpretation and context.
R2-9	I am unsure whether calculating the benefit-cost ratio is appropriate because not all costs and benefits are considered. Adding new costs or benefits may change the qualitative conclusions.	Thank you for raising this critical concern. We agree that incorporating additional costs and benefits could impact the overall conclusions. **On the cost side,** In Chinese cities, traffic data are collected from various public and private sectors, each with distinct collection and processing costs. Multi-source data sharing and cross-validation can significantly lower the installation and maintenance costs of traffic detectors. For example, data from private or public entities like ride-hailing platforms (e.g., Didi) can complement or even substitute the need for installing traffic detectors at certain intersections. However, cross-sector data sharing often involves substantial coordination expenses, which are difficult to quantify consistently. In our analysis, we adopt a conservative approach by assuming relatively high implementation costs, reflecting the current challenges of elevated cross-sector coordination expenses and the necessity of traffic detection at nearly all intersections. **On the benefit side,** reductions in air pollutants, traffic accidents and noise from smoother traffic flow are complex to measure accurately. This makes our benefit-cost ratio likely conservative, as it may not fully capture both the potential savings from data-sharing approaches and the broader societal and environmental benefits. By adopting a higher cost estimation and a lower benefit estimation, our analysis likely underestimates the overall cost-effectiveness of adaptive traffic signals. While it may not account for every potential cost and benefit, the study provides a valuable benchmark for large cities aiming to mitigate congestion and emissions. Our findings highlight the potential of integrating big-data-enabled adaptive signals with complementary "Avoid-Shift-Improve" strategies, offering practical guidance for cities seeking economically viable and environmentally sustainable traffic management solutions. We have addressed your concerns by revising the content in the "Cost and Benefit" and "Discussion" sections. The specific changes are detailed below. **Results – Cost and benefit (Line 227-292):** "To effectively mitigate congestion and emissions, adaptive traffic signals require a comprehensive evaluation of both implementation costs and

		resulting benefits (Fig. 4a–d). The most substantial cost component - real-time traffic detection - demands continuous traffic volume data, which incurs considerable expense. Our estimates suggest that achieving the targeted congestion mitigation across 100 cities would necessitate a total investment of approximately US$1.48 billion, covering initial setup and ongoing maintenance (Fig. 4f). Specifically, based on an analysis of 145 recent field cases, the initial installation cost for traffic detectors is projected at US$1.31 billion, assuming a 71-month lifespan per detector[36]. Additionally, annual operation and maintenance costs are estimated at around US$0.17 billion. Unsurprisingly, larger cities bear higher costs due to the scale of intersections and network density. **Integrating multiple existing data sources can possibly reduce implementation costs.** Using a combination of inductive-loop detectors, surveillance cameras, and floating car data allows for data substitution at intersections lacking traffic detectors (Extended Data Table 2). Yet, deploying these solutions is often complex due to varied ownership of traffic detectors and signals across public and private entities. We classify multi-source data integration solutions into three tiers: (1) Departmental solutions with low barriers using single-department data; (2) Cross-sector solutions requiring interdepartmental collaboration and policy support; and (3) Public-private partnerships, offering broader data coverage at higher implementation barriers. **Higher-tier solutions promise less traffic detection costs but entail coordination costs difficult to quantify. Centralized smart city systems, such as City Brain, highlight the potential of cross-sector data-sharing to lower detection implementation costs while supporting networked governance**[37] for targeted deployment from high- to low-traffic areas (Extended Data Fig. 5). The societal benefits of adaptive traffic signals are substantial, primarily from reductions in travel time and fuel consumption. Based on stated preference (SP) survey data of travelers' willingness to pay for reduced travel times in China[38], time savings are valued at approximately US$1.56 billion annually. Increased travel speeds further contribute to reductions in fuel consumption, yielding an estimated US$15.83 billion in annual fuel savings (Fig. 4f). Additionally, adaptive signals generate environmental benefits, with CO_2 emissions reductions valued at approximately US$14.44 billion annually. In addition to CO_2, adaptive signals help mitigate air pollutants such as NO_x, NH_3, and VOCs, which contribute to PM2.5 and O_3 pollution, as well as traffic accident and noise. **The full scope of these environmental benefits is challenging to quantify accurately, meaning the actual value could be even higher. Nevertheless, our estimates align with China's carbon-neutral policy priorities, reinforcing the relevance of adaptive traffic signals in environmental policy.**

		Collectively, adaptive signals can deliver societal and environmental benefits of approximately US$31.82 billion per year across the 100 cities, representing a benefit-cost ratio of about 21.6. This compelling ratio underscores adaptive traffic signals as a highly effective strategy for urban congestion mitigation and environmental improvement. Individual city assessments reveal significant variability, with benefit-cost ratios exceeding 30 in half of the 100 cities, and nearly a quarter showing ratios above 50 (Fig. 4e). These high ratios are largely driven by fuel savings and CO_2 reductions, while travel time benefits and implementation costs are relatively consistent across cities. Cities such as Urumqi and Yili, however, may not experience immediate net cost benefits from travel-time savings alone, with a benefit-cost ratio below 1/3 (Extended Data Fig. 4). Yet, when broader societal and environmental gains are factored in, these cities see overall benefits exceeding costs by more than 20 times, primarily due to emissions reductions and fuel savings. **These findings indicate that cities focused narrowly on congestion alleviation may benefit from adopting a more comprehensive view, as our study highlights the substantial societal and environmental co-benefits of adaptive signals.** Despite these promising outcomes, many pilot projects in China - such as those in Hangzhou and Nanchang - still concentrate predominantly on congestion reduction, often overlooking broader environmental and fuel-saving benefits. This gap arises partly due to the complexities of estimating city-wide emissions reductions. Our analysis provides critical insights into these co-benefits, underscoring the strategic potential of adaptive traffic signals to support urban sustainability and inform policy adjustments for broader implementation across Chinese megacities." **Discussion (Line 309-319):** "Our benefit-cost analysis may understate adaptive traffic signals' value due to limitations in data availability. First, implementation costs could be overestimated; cities in China increasingly utilize floating car data from multiple sources from navigation and ride-hailing apps (e.g., Gaode Map, Didi), potentially reducing installation costs of traffic detectors at intersections with high floating car penetration. However, lacking comprehensive data, we could not quantify this impact. Second, we did not account for co-benefits such as noise reduction and accident mitigation associated with smoother traffic flow. Despite these limitations, our analysis provides a robust reference for policymakers, with opportunities to refine benefit-cost accuracy as more comprehensive data become available. Importantly, our findings support the adoption of adaptive traffic signals as a valuable tool for urban sustainability and emission reduction, even with conservative estimates."

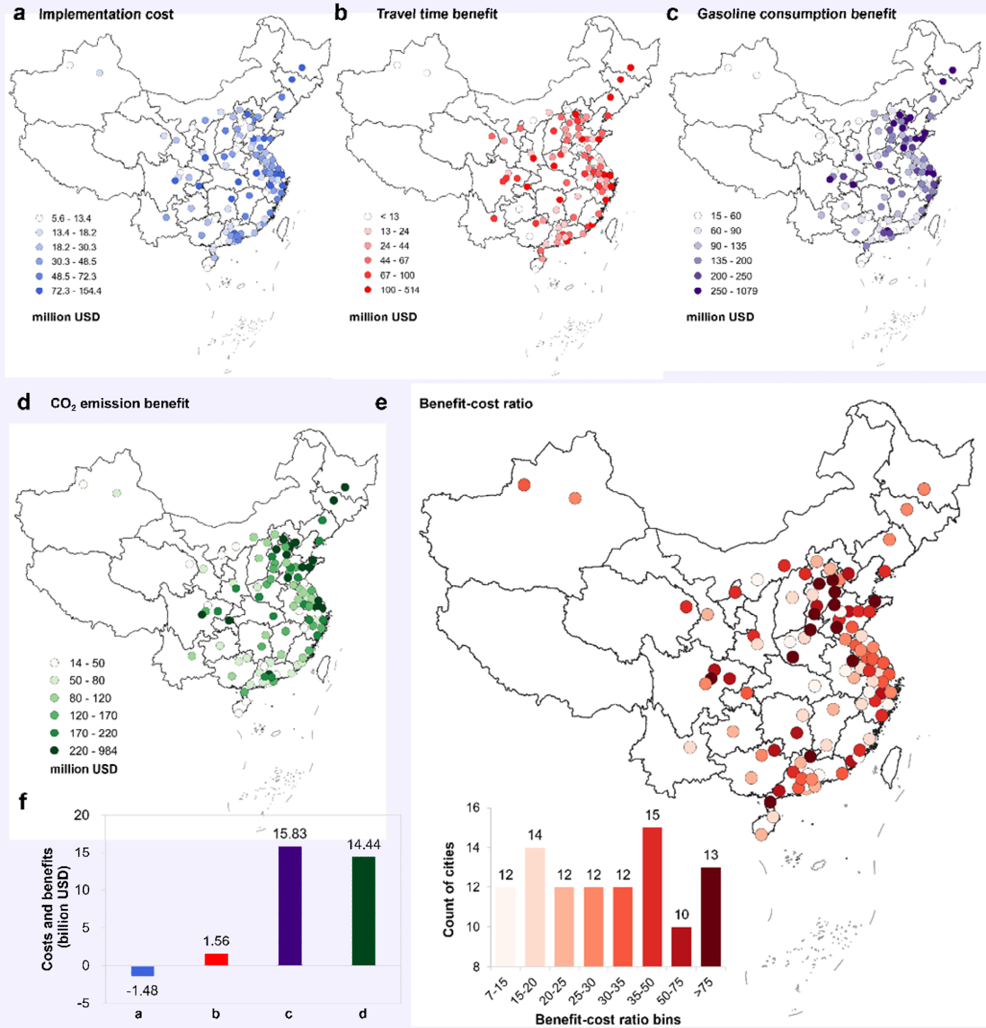
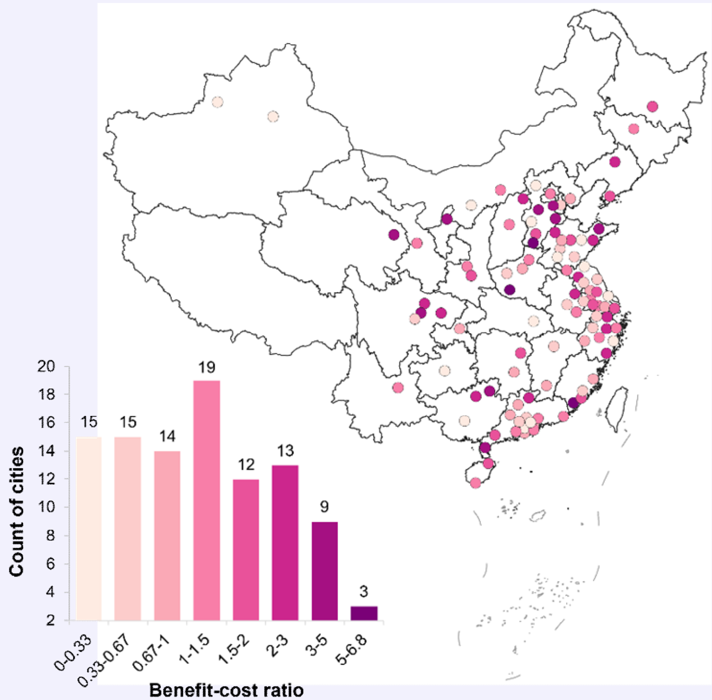


Fig. 5 | Costs and benefits of implementing adaptive traffic signal control. a – d, Geographic distribution of costs and benefits across cities: implementation cost (including installation and maintenance of traffic detectors) (**a**), benefits from reduced travel time (**b**), reduced gasoline consumption (**c**), and reduced CO_2 emissions (**d**). **e**, Benefit-cost ratios across 100 cities. **f**, Net costs and benefits in 100 cities, with negative values representing costs and positive values representing

		benefits. The base map is applied without endorsement from GADM data (https://gadm.org/).  **Extended Data Fig. 5 | Benefit-cost ratios across 100 cities based on travel time savings as the sole societal benefit.**
R2-10	The content of Policy Implications does not seem to be related to the Results. In other words, it seems like the current Policy Implications could also be written without the results conducted in this paper.	Thank you for highlighting this important issue. In response, we have restructured the original "Policy Implications" section and renamed it the "Discussion" section in the revised version. Previously, the "Policy Implications" section explored the policy and technical feasibility of implementing adaptive traffic signals. We have streamlined this content and incorporated it into the "Cost and benefit" section to ensure closer alignment with our study's findings. In the new "Discussion" section, we provide a summary of our key findings, acknowledge study limitations, and suggest directions for future research to further examine the potential of big data and other tools to reduce urban transportation emissions under the "Avoid-Shift-Improve" framework. This enhanced "Discussion" ties our study back to the broader scientific context and

		illustrates how our findings advance or challenge current perspectives on the impact of big data on congestion and emissions mitigation. We believe this new structure creates a more cohesive connection between our results. The corresponding revisions are listed below. **Discussion (Line 294–330):** "China's urbanization rate is projected to rise from 62.5% in 2021 to 80% by 2050, with increased migration to mega-cities posing both challenges for congestion and opportunities for decarbonization. Advances in data collection and processing now make adaptive traffic signals a practical solution for managing congestion and reducing urban emissions. **This study introduces a systematic framework for modeling and assessing the benefits of big-data-driven adaptive traffic signals at a city-wide scale, particularly in megacities with populations exceeding 10 million. Our findings indicate that, while travel time reductions and implementation costs of adaptive traffic signals are often similar, the emissions reduction benefits tend to outweigh the costs.** Even in cities such as Sanya, Yili, and Urumqi, where gains in travel speed and emissions may be more modest, our study provides valuable insights. These cities can apply our framework to evaluate the broader societal and environmental advantages of adaptive traffic signals, even potentially informing policy shifts to leverage big data for targeted transport emission reduction goals. Our benefit-cost analysis may understate adaptive traffic signals' value due to limitations in data availability. First, implementation costs could be overestimated; cities in China increasingly utilize floating car data from multiple sources from navigation and ride-hailing apps (e.g., Gaode Map, Didi), potentially reducing installation costs of traffic detectors at intersections with high floating car penetration. However, lacking comprehensive data, we could not quantify this impact. Second, we did not account for co-benefits such as noise reduction and accident mitigation associated with smoother traffic flow. **Despite these limitations, our analysis provides a robust reference for policymakers, with opportunities to refine benefit-cost accuracy as more comprehensive data become available. Importantly, our findings support the adoption of adaptive traffic signals as a valuable tool for urban sustainability and emission reduction, even with conservative estimates.** With road transport contributing 11.9% of global CO_2 emissions and ranking among the top three emitting sectors worldwide (Extended Data Fig. 1), data-driven congestion mitigation solutions

		offer significant potential for supporting China's carbon neutrality and sustainable development goals (SDGs). Future research could expand on our framework by examining the emission reduction potential of integrated "Avoid-Shift-Improve" solutions. For instance, further studies could explore "Improve" measures like big-data empowered dynamic variable lanes and green wave coordination, "Shift" strategies such as transit-oriented development, and "Avoid" approaches like the 15-minute city concept. Our framework and models provide a foundation for assessing city-wide congestion and emissions reduction strategies, aligning with broader efforts toward urban sustainability."
R2-11	GHSL-UCDB (mentioned in Line 398) should be defined in Line 271.	Thank you for highlighting this point. We agree that the definition of GHSL-UCDB should be clarified. The Global Human Settlement Layer (GHSL) project, supported by the European Commission's Joint Research Centre and the Directorate-General for Regional and Urban Policy, provides key data for analyzing urban environments. The GHS Urban Centre Database (GHS-UCDB) defines "urban centers" based on multitemporal thematic attributes derived from GHSL data and other open scientific sources. The corresponding revisions are listed below. **Methods – Data sources (Line 333–345):** "We used data from OpenStreetMap to obtain road networks in cities (available at https://www.openstreetmap.org/). The urban area boundary, population, and GDP data were retrieved from the GHS Urban Centre Database (available at https://ghsl.jrc.ec.europa.eu/ghs_stat_ucdb2015mt_r2019a.php). The GHS Urban Centre Database (GHS-UCDB) describes spatial entities called "urban centers" according to a set of multitemporal thematic attributes gathered from the GHSL sources integrated with other sources available in the open scientific domain. The Urban Centres are defined by specific cut-off values on resident population and built-up surface share in a 1x1 km uniform global grid. We manually adjusted the errors in boundaries of some cities like Guangzhou and Hangzhou based on OpenStreetMap. The top 100 congested cities in China and the associated speed data were retrieved from Gaode during the period from 2022/11/02 to 2022/11/08 (available at https://report.amap.com/diagnosis/index.do). Information on pilot projects in Hangzhou and Nanchang was obtained from online reports and studies[28,30]."

Referee #3

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<tr><th colspan="2">Comment</th><th>Response and Change</th></tr>
<tr><td>R3-1</td><td>I co-reviewed this manuscript with one of the reviewers who provided the listed reports. This is part of the Nature Communications initiative to facilitate training in peer review and to provide appropriate recognition for Early Career Researchers who co-review manuscripts</td><td>Thank you for co-reviewing our study. We have carefully addressed your feedback along with the comments from other reviewers, resulting in the following key revisions in the newly submitted manuscript:

1. Research Contributions and Context: We expanded the Introduction to situate our contributions within recent advancements in adaptive traffic signal control, focusing on the large-scale impact of big-data-enabled adaptive signals on congestion and emissions in Chinese megacities.
2. Adaptive Signals and Emission Reduction: We revised the Introduction to highlight that urban congestion contributes 12.7–14.2% of emissions in major Chinese cities. Additionally, a supplementary simulation using the MOVES model further quantifies the impact of adaptive signals on reducing transport emissions.
3. Enhanced Emissions Estimation Model: We refined our emissions model with updated data and additional simulations, strengthening the robustness and reliability of our findings.
4. Broadened Discussion for Scientific Relevance: We restructured and expanded the “Policy Implications” section, now titled “Discussion,” to synthesize our findings, address limitations, and outline future research directions within the “Avoid-Shift-Improve” framework, emphasizing policy implications and the role of big data in emissions reduction.

Thank you again for your insightful contributions, which have helped us to significantly improve our manuscript.</td></tr>
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Referee #4

Comment		Response and Change
R4-1	The paper explores the impact of implementing adaptive traffic signal control systems in reducing urban congestion and carbon emissions. The study focuses on the top 100 most congested cities in China, using data from OpenStreetMap and Gaode Map for road network and travel speed data. The authors propose an adaptive signal control method that leverages real-time traffic data to optimize traffic flow and reduce emissions. The paper includes simulated experiments to demonstrate the potential benefits of this approach, such as significant reductions in trip times, fuel consumption, and CO_2 emissions.	Thank you for your positive feedback. Our study presents a comprehensive framework to assess the system-wide impacts of big-data-enabled adaptive traffic signals on reducing congestion and emissions across the 100 most congested Chinese cities. Our findings indicate that while adaptive signals can deliver travel-time reductions comparable to data acquisition and processing costs, the overall benefits—including broader societal and environmental impacts—far exceed these costs by over 20 times, primarily due to emissions reductions and fuel savings. We believe our study can inform a potential policy shift toward leveraging big data for targeted emissions reductions in urban mobility, especially for cities currently focused solely on congestion reduction. The corresponding revisions are listed below. **Introduction (Line 63–95):** "Research on adaptive traffic signal control has progressed over decades, evolving from early heuristic methods to data-intensive reinforcement learning approaches[15,16]. Adaptive control methods fall into two primary categories: cycle-based methods (e.g., Webster's algorithm[17–19], SCATS and SCOOT[20,21]) and phase-based methods (e.g., max-pressure[22–24] and reinforcement learning algorithms[25–27]). Cycle-based methods, which maintain consistent phase settings, are widely used because they require less data and provide straightforward rules for drivers to follow. Phase-based methods, which adjust phases in real time, offer greater adaptability but face challenges in Chinese cities where timely, high-quality data are often limited, and local driving and pedestrian behaviors require careful consideration. Although multi-source traffic data is now available, collecting and processing this data remains costly and can sometimes be unreliable. Therefore, signal timing update methods that are less data-dependent and more robust to data errors are still essential. In this context, it is not the novelty of traffic control algorithms but rather their compatibility with available data that becomes crucial. Consequently, simpler cycle-based algorithms like Webster's method have gained traction in China, particularly when integrated with platforms such as City Brain[28,29]. Pilot projects in Hangzhou and Nanchang have shown over 15% reductions in trip delays[30], demonstrating adaptive control's potential in lifting long-standing traffic restrictions without increasing congestion.

		While pilot projects and extensive research on isolated intersections[31,32] show promise, systematic studies on the city-wide impacts of adaptive traffic signals - particularly considering both congestion and emissions reduction - are still limited. **To our knowledge, this study is the first to evaluate the large-scale implementation of big-data-driven adaptive signals in megacities, specifically focusing on urban areas with populations exceeding 10 million and thousands of signalized intersections.** We address this research gap by conducting simulations in China's 100 most congested cities, using OpenStreetMap[33] for road data and Gaode Map for traffic speed data. Our analysis quantifies congestion and emission reductions at both isolated intersection and city-wide levels, identifies key socioeconomic and infrastructure factors influencing congestion mitigation, and assesses the cost-effectiveness of adaptive signal systems. Through this comprehensive examination of city-scale adaptive traffic signals, our study advances the understanding of smart traffic management and offers insights for developing low-emission, efficient urban mobility solutions aligned with China's sustainability targets."
R4-2	The work is significant as it addresses a pressing issue in urban planning and transportation engineering by providing a scalable and cost-effective solution to traffic congestion. The proposed method builds on previous studies, such as extending works on adaptive traffic signal control using dynamic programming and real-time systems like City Brain and also includes a benefit-cost analysis.	Thank you for raising this critical concern. We agree that incorporating additional costs and benefits could impact the overall conclusions. **On the cost side,** In Chinese cities, traffic data are collected from various public and private sectors, each with distinct collection and processing costs. Multi-source data sharing and cross-validation can significantly lower the installation and maintenance costs of traffic detectors. For example, data from private or public entities like ride-hailing platforms (e.g., Didi) can complement or even substitute the need for installing traffic detectors at certain intersections. However, cross-sector data sharing often involves substantial coordination expenses, which are difficult to quantify consistently. In our analysis, we adopt a conservative approach by assuming relatively high implementation costs, reflecting the current challenges of elevated cross-sector coordination expenses and the necessity of traffic detection at nearly all intersections. **On the benefit side,** reductions in air pollutants, traffic accidents and noise from smoother traffic flow are complex to measure accurately. This makes our benefit-cost ratio likely conservative, as it may not fully capture both the potential savings from data-sharing approaches and the broader societal and environmental benefits. By adopting a higher cost estimation and a lower benefit estimation, our analysis likely

		underestimates the overall cost-effectiveness of adaptive traffic signals. While it may not account for every potential cost and benefit, the study provides a valuable benchmark for large cities aiming to mitigate congestion and emissions. Our findings highlight the potential of integrating big-data-enabled adaptive signals with complementary "Avoid-Shift-Improve" strategies, offering practical guidance for cities seeking economically viable and environmentally sustainable traffic management solutions. The corresponding revisions are provided in the "Cost and benefit" and "Discussion" sections.
R4-3	The methodology is sound and meets the expected standards. The use of simulation-based experiments demonstrates a rigorous approach. The benefit-cost ratios and the detailed regression analysis between speed improvement and city indicators validate the effectiveness of the proposed method. The paper provides sufficient details for replication by including a description of data sources, experiment setup, and the adaptive signal control algorithm. In addition, the description of the simulation environment and the steps taken to generate synthetic trips ensures that other researchers can reproduce the study's findings with similar datasets.	Thank you for your positive comments on the methodology and datasets used in our study. We have further improve the robustness and reliability of our methods with following adjustments: 1. **Updated emissions data.** We have updated our business-as-usual (BAU) emissions baseline using the most recent 2021 data from the Climate Watch Database for China. While the 2021 dataset reflects more current vehicle emissions and reduces the risk of overestimation, it is also widely cited and recognized as highly reliable for emissions studies, ensuring consistency in our comparative analysis. 2. **Refined emission estimation model.** we adopted the latest version of the Motor Vehicle Emission Simulator (MOVES), MOVES4 (released by the U.S. Environmental Protection Agency in 2023), which provides a more robust and scientifically validated framework for emissions estimation. MOVES4's extensive validation and application in both research and regulatory contexts underscore its reliability, making it a solid foundation for the conclusions in our study. The corresponding revisions are provided in the "Transport emission" subsection of the "Methods" section. (Line 468–507)
R4-4	Additional references suggested: Lertworawanich P., Unhasut P., A CO emission-based adaptive signal control for isolated intersections, Journal of the Air and Waste Management Association, 2021, 71 (5), pp. 564 - 585, DOI:	Thank you for your helpful suggestions. The recommended articles have enhanced our understanding of leveraging big data to adapt traffic signals to flow dynamics and the potential impacts of adaptive signals at isolated intersections. In alignment with these studies, our research examines the broader impact of implementing adaptive traffic signal control systems on reducing urban congestion and carbon emissions at the city scale, with a focus on large cities with over 10 million residents and

	10.1080/10962247.2020.1862940 Li X., Li G., Pang S.-S., Yang X., Tian J.,Signal timing of intersections using integrated optimization of traffic quality, emissions and fuel consumption: A note, Transportation Research Part D: Transport and Environment, 9 (5), 2004, pp. 401 - 407, DOI: 10.1016/j.trd.2004.05.001 Chiara Bachechi, Laura Po, Federica Rollo, Big Data Analytics and Visualization in Traffic Monitoring, Big Data Research, Volume 27, 2022, 100292, ISSN 2214-5796, https://doi.org/10.1016/j.bdr.2021.100292.	thousands of intersections. We have thoroughly reviewed the three recommended articles, as well as related studies, and incorporated them into the “Introduction” section of our updated submission. The corresponding revisions are listed below. **Introduction (Line 48 - 95):** “Efforts to mitigate urban congestion and transport emission can be classified under the "Avoid-Shift-Improve" (ASI) framework[7]. The "Avoid" strategies aim to reduce travel demand through compact urban planning and policies like congestion pricing and traffic restrictions[8–10]. The "Shift" strategies encourage a shift from private vehicles to sustainable modes such as public transit, cycling and walking, often supported by transit-oriented development (TOD) initiatives[11,12]. While both "Avoid" and "Shift" strategies require significant investment in infrastructure or policy changes, which can be time- and cost-intensive, the "Improve" strategies focus on enhancing the efficiency of existing transport systems, often offering immediate congestion relief. Adaptive traffic signal control exemplifies an “Improve” strategy, optimizing traffic flow by dynamically adjusting signal timings and reducing the need for expanded road capacity. **Recent advances in big-data collection and processing techniques have enabled cities to implement adaptive signals on a large scale[13,14], making real-time adjustments possible and enhancing overall traffic management**. Research on adaptive traffic signal control has progressed over decades, evolving from early heuristic methods to data-intensive reinforcement learning approaches[15,16]. Adaptive control methods fall into two primary categories: cycle-based methods (e.g., Webster’s algorithm[17–19], SCATS and SCOOT[20,21]) and phase-based methods (e.g., max-pressure[22–24] and reinforcement learning algorithms[25–27]). Cycle-based methods, which maintain consistent phase settings, are widely used because they require less data and provide straightforward rules for drivers to follow. Phase-based methods, which adjust phases in real time, offer greater adaptability but face challenges in Chinese cities where timely, high-quality data are often limited, and local driving and pedestrian behaviors require careful consideration. Although multi-source traffic data is now available, collecting and processing this data remains costly and can sometimes be unreliable. Therefore, signal timing update methods that are less data-dependent and more robust to data errors are still essential. In this context, it is not the novelty of traffic control

		algorithms but rather their compatibility with available data that becomes crucial. Consequently, simpler cycle-based algorithms like Webster's method have gained traction in China, particularly when integrated with platforms such as City Brain[28,29]. Pilot projects in Hangzhou and Nanchang have shown over 15% reductions in trip delays[30], demonstrating adaptive traffic signal control's potential in lifting long-standing traffic restrictions without increasing congestion. **While pilot projects and extensive research on isolated intersections[31,32]** show promise, systematic studies on the city-wide impacts of adaptive traffic signals - particularly considering both congestion and emissions reduction - are still limited. To our knowledge, this study is the first to evaluate the large-scale implementation of big-data-driven adaptive signals in megacities, specifically focusing on urban areas with populations exceeding 10 million and thousands of signalized intersections. We address this research gap by conducting simulations in China's 100 most congested cities, using OpenStreetMap[33] for road data and Gaode Map for traffic speed data. Our analysis quantifies congestion and emission reductions at both isolated intersection and city-wide levels, identifies key socioeconomic and infrastructure factors influencing congestion mitigation, and assesses the cost-effectiveness of adaptive signal systems. Through this comprehensive examination of city-scale adaptive traffic signals, our study advances the understanding of smart traffic management and offers insights for developing low-emission, efficient urban mobility solutions aligned with China's sustainability targets."