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International Telecommunication Union
Standardization Sector

Recommendation

ITU-T L.1640 (02/2024)

SERIES L: Environment and ICTs, climate change, e-waste, energy efficiency; construction, installation and protection of cables and other elements of outside plant

Circular and sustainable cities and communities

Methodology for dynamic monitoring and analysis of greenhouse gas emissions in cities

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Recommendation ITU-T L.1640

Methodology for dynamic monitoring and analysis of greenhouse gas emissions in cities

Summary

Recommendation ITU-T L.1640 presents the necessary conditions for implementing near-real-time greenhouse gas (GHG) monitoring in cities, with updates provided shortly after data collection rather than instantly (real-time), to support the sustainable development strategy and planning of the city. Compared to existing research or standards, near-real-time greenhouse gas data in cities can present high temporal resolution characteristics of urban emissions (hourly or daily), enabling better identification of spatial and temporal hotspots. This can help city managers formulate more effective emission reduction policies.

Recommendation ITU-T L.1640 presents the general principles on data collection, data processing, data fusion, and monitoring and analysing of GHG emissions of cities and outlines the different methodologies that are being developed:

– Sources for near-real-time city data collection, and its processing and fusing.
– Key steps for city near-real-time GHG calculation and attribution analysis.
– Optimization strategy for city sustainable planning.

History*

Edition	Recommendation	Approval	Study Group	Unique ID
1.0	ITU-T L.1640	2024-02-22	5	11.1002/1000/15770

Keywords

Attribution analysis, dynamic monitoring, GHG emission, optimization strategy.

* To access the Recommendation, type the URL https://handle.itu.int/ in the address field of your web browser, followed by the Recommendation's unique ID.

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The approval of ITU-T Recommendations is covered by the procedure laid down in WTSA Resolution 1.

In some areas of information technology which fall within ITU-T's purview, the necessary standards are prepared on a collaborative basis with ISO and IEC.

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Methodology for dynamic monitoring and analysis of greenhouse gas emissions in cities

1 Scope

This Recommendation proposes to introduce the methodology for dynamic monitoring and analysis for greenhouse gas (GHG) emissions, including:

– GHG emission data collection;

– GHG emission data processing;

– GHG emission data fusion;

– GHG emission data application including GHG emission calculation and analysis and GHG emission changes attribution analysis.

2 References

The following ITU-T Recommendations and other references contain provisions which, through reference in this text, constitute provisions of this Recommendation. At the time of publication, the editions indicated were valid. All Recommendations and other references are subject to revision; users of this Recommendation are therefore encouraged to investigate the possibility of applying the most recent edition of the Recommendations and other references listed below. A list of the currently valid ITU-T Recommendations is regularly published. The reference to a document within this Recommendation does not give it, as a stand-alone document, the status of a Recommendation.

[ITU-T L.1400] Recommendation ITU-T L.1400 (2023), *Overview and general principles of methodologies for assessing the environmental impact of information and communication technologies*.

[ITU-T L.1410] Recommendation ITU-T L.1410 (2014), *Methodology for environmental life cycle assessments of information and communication technology goods, networks and services*.

[ITU-T L.1420] Recommendation ITU-T L.1420 (2012), *Methodology for energy consumption and greenhouse gas emissions impact assessment of information and communication technologies in organizations*.

[ITU-T L.1430] Recommendation ITU-T L.1430 (2013), *Methodology for assessment of the environmental impact of information and communication technology greenhouse gas and energy projects*.

[ITU-T L.1440] Recommendation ITU-T L.1440 (2015), *Methodology for environmental impact assessment of information and communication technologies at city level.*

[ITU-T L.1450] Recommendation ITU-T L.1450 (2018), *Methodologies for the assessment of the environmental impact of the information and communication technology sector.*

[ISO 14064-1] ISO 14064-1:2006, *Greenhouse gases – Part 1: Specification with guidance at the organization level for quantification and reporting of greenhouse gas emissions and removals*.

[ISO 14064-2] ISO 14064-2:2006, *Greenhouse gases – Part 2: Specification with guidance at the project level for quantification, monitoring and reporting of greenhouse gas emission reductions or removal enhancements*.

[ISO 14064-3] ISO 14064-3:2006, *Greenhouse gases – Part 3: Specification with guidance for the validation and verification of greenhouse gas assertions*.

[ISO 14067] ISO 14067:2018 (E), *Greenhouse gases – Carbon footprint of products – Requirements and guidelines for quantification*.

3 Definitions

3.1 Terms defined elsewhere

This Recommendation uses the following terms defined elsewhere:

3.1.1 greenhouse gases (GHGs) [ITU-T L.1410]: For the purposes of this methodology, GHGs are the seven gases listed in the Kyoto Protocol:

– carbon dioxide (CO2)

– methane (CH4)

– nitrous oxide (N2O)

– hydrofluorocarbons (HFCs)

– perfluorocarbons (PFCs)

– sulphur hexafluoride (SF6)

– nitrogen trifluoride (NF3)

3.1.2 near-real-time [b-Zhu 1]: Computation activities provided shortly after data collection rather than instantly (real-time).

3.2 Terms defined in this Recommendation

This Recommendation defines the following terms:

3.2.1 dynamic monitoring: Monitoring and detecting the daily temporal and spatial variation of greenhouse gas (GHG) emission data using multi-source data.

3.2.2 continuous emission monitoring system (CEMS): Total equipment necessary for the determination of greenhouse gas (GHG) emission rate using pollutant analyser measurements and a conversion equation, graph, or computer program to produce results in units of the applicable emission limitation or standard.

4 Abbreviations and acronyms

This Recommendation uses the following abbreviations and acronyms:

CEMS Continuous Emission Monitoring System

EPA United States Environmental Protection Agency

EU ETS European Union Emissions Trading System

GHG Greenhouse Gas

GIS Geographic Information System

IEA International Energy Agency

NILM Non-intrusive Load Monitoring

OCO Orbiting Carbon Observatory

SDGs Sustainable Development Goals

TROPOMI Tropospheric Monitoring Instrument

5 Conventions

None.

6 Method framework for dynamic monitoring and analysis of GHG emissions

The method for dynamic monitoring and analysis of greenhouse gas (GHG) emissions can be divided into four parts: data collection, data processing, data fusion and application, is shown in Figure 1. Data collection refers to raw data collection, which includes traditional data collection and multiple sources of data collection. Data processing refers to raw data cleaning, filtering and normalization, which improves raw data quality and extracts emission-related information for further calculation. Data fusion refers to the combination of all the processed data and estimate missing data. Application refers to near-real-time GHG emission calculation and analysis, which enables GHG dynamic monitoring and timely attribution analysis for public management.

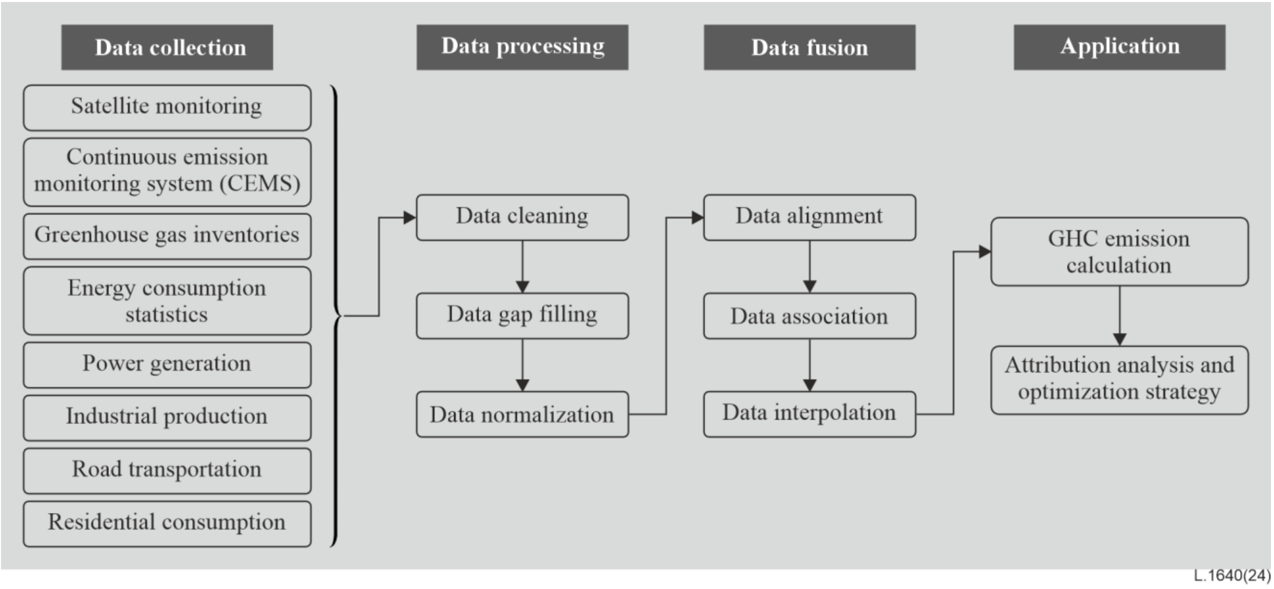


Figure 1 – Method Framework for dynamic monitoring and analysis of GHG emissions

7 GHG emission data collection

At the city level, GHG emissions can be categorized into various sectors based on their sources, such as power generation, industrial production, transportation, and residential heating. In some instances, direct measurement of GHG emissions is feasible through top-down approaches, such as the installation of continuous monitoring equipment at factory emission outlets or satellite monitoring of GHG emissions. However, these measurement methods are often limited by the prohibitive cost of monitoring equipment, or the high level of uncertainty associated with satellite monitoring. Therefore, GHG accounting in cities mostly relies on energy consumption statistics or other related proxy data to track and estimate emissions, following GHG accounting guidance developed by esteemed organizations such as the Intergovernmental Panel on Climate Change (IPCC) and GHG Protocol.

Generally, the sources of city-level GHG emission data are shown in Table 1.

Table 1 – GHG emission data sources city-level

Type	Potential sources	Frequency	Description for usage
Satellite monitoring	Scientific communities	Days	Satellite monitoring can be used to obtain atmospheric greenhouse gas column concentrations, and combined with meteorological and other parameters, inverse models can be used to calculate greenhouse gas emissions from cities or factories.
Continuous emission monitoring system (CEMS)	Factories / Environment regulatory agencies	Minute(s)	Factories equipped with CEMS devices can obtain real-time greenhouse gas emissions from factory chimneys and report them to urban regulatory agencies in real-time.
Greenhouse gas inventories	Government/regulatory agencies	Quarter to Year	Cities regularly compile quarterly or annual greenhouse gas inventories, but there is generally a lag of more than one year. Due to the relatively authoritative data sources of greenhouse gas inventories, they can be used to correct historical greenhouse gas data for cities.
Energy consumption statistics	Statistical agencies	Month to Year	They can be used to calculate carbon emissions in cities by multiplying the city's energy consumption by the corresponding emission parameters according to inventory compilation guidelines such as IPCC or GHG Protocol.
Power generation	Public service sectors (power grid/companies)	Minute to Month	When fuel consumption statistics for the power sector are unavailable, fuel consumption for power generation can be estimated using electricity production data.
Industrial production	Industry association / Statistical agencies	Week to Month	When fuel consumption statistics for the industrial sector are unavailable, fuel consumption for industrial production can be estimated using industrial production data (such as industrial product output).
Road transportation	Transportation regulatory departments	Minute to Month	When fuel consumption statistics for the transportation sector are unavailable, fuel consumption for the transportation sector can be estimated using traffic volume or road congestion.
Residential consumption	Public service sectors (natural gas suppliers/smart meters)	Minute to Month	When natural gas consumption data is lacking, heating or cooling demand for residents can be estimated using temperature data.

Detailed information on the data sources is listed and shown in Figure 2.

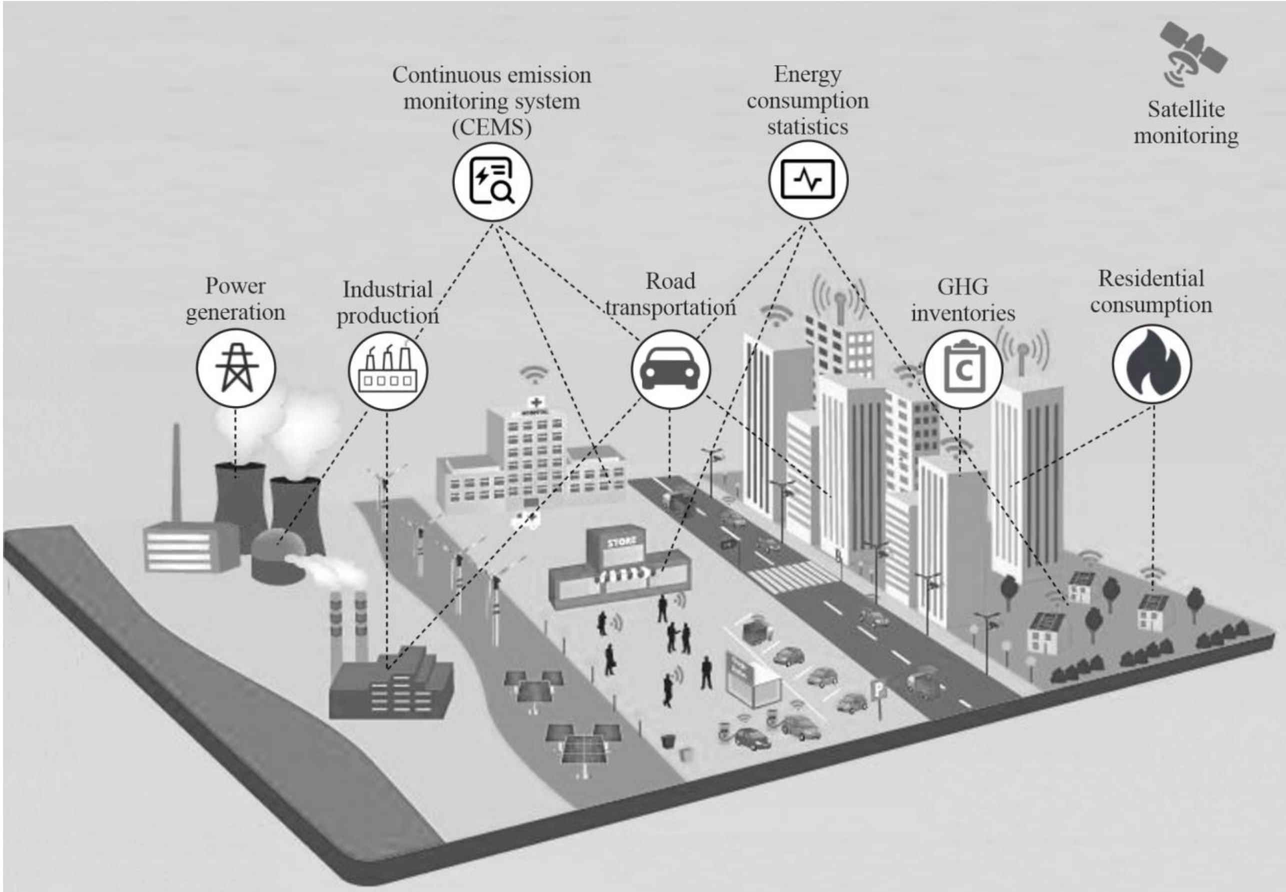


Figure 2 – GHG emission data collection of the city

a) Satellite monitoring: Satellite monitoring is a remote sensing technique that uses satellite sensors to measure GHG concentrations in the atmosphere. These sensors can detect GHG signatures such as CO2, CH4, and N2O from space, providing a global view of GHG concentrations and their sources. One example of a satellite mission dedicated to GHG observation is the Orbiting Carbon Observatory (OCO) mission by NASA. The OCO satellite uses a spectrometer to measure the absorption of sunlight at different wavelengths, which can be used to determine carbon dioxide concentrations in the atmosphere. Other satellite missions that can provide complementary information on GHG emissions include the Tropospheric Monitoring Instrument (TROPOMI) on the European Space Agency's Sentinel-5P satellite, which can detect methane emissions from sources such as oil and gas facilities.

b) Continuous emission monitoring system (CEMS): The CEMS is an approach to measuring GHG emissions that involves using real-time or near-real-time monitoring equipment installed at industrial facilities, power plants, or other stationary sources of emissions. These monitoring systems continuously measure and record emissions data, providing a more comprehensive and accurate picture of GHG emissions compared to periodic or occasional measurements. The data collected by CEMS can typically be accessed through government agencies responsible for regulating emissions from industrial facilities, such as the United States Environmental Protection Agency (EPA) or the European Union Emissions Trading System (EU ETS). These agencies generally maintain databases or online portals where the public can access data on emissions from regulated facilities. Additionally, some power companies or industrial facilities may publish their emissions data, including GHG emissions, on their websites or in sustainability reports.

c) Greenhouse gas inventory: Greenhouse gas inventories record information on the amount, composition, and location of greenhouse gas emissions and absorption caused by human activities. These inventories can be obtained through:
   i) Government-led organizations and compilations of greenhouse gas inventories, which are usually prepared and published on a regular basis by government departments such as administration, statistics, energy, and environmental protection.
   ii) Greenhouse gas inventory data regularly reported by companies to the government.

d) Energy consumption statistics:
   i) Official energy consumption statistics published by government statistical agencies, usually on an annual or quarterly basis.
   ii) Energy consumption statistics collected and published by institutions such as the International Energy Agency (IEA) and the World Bank, usually on an annual or monthly basis.

e) Power generation: Data on electricity production or consumption by source or end-use, regularly compiled and published by official electricity joint organizations or power generation companies, usually on a daily or hourly basis.

f) Road transportation: Traffic flow data from road counting sensors or global positioning system (GPS) information records, or road traffic data such as traffic flow and road congestion indices estimated by map navigation vendors based on user location data, which can reflect road traffic flow information, usually on a daily, hourly, or minute-by-minute basis.

g) Industrial production: Production of high-carbon industrial products (such as cement, steel), or industrial production indices.

h) Residential consumption: Natural gas consumption data for residential living, regularly compiled and published by natural gas supply companies, usually on a daily or hourly basis.

8 GHG emission data processing

Due to the fact that urban GHG data usually comes from different sources, the collected raw data needs to be further cleaned, organized, and standardized in order to establish a unified data set for subsequent analysis. Specifically, this includes:

a) Data cleaning: Data cleaning is the first step in data processing, which mainly involves selecting, deduplicating, filling missing values, and handling outliers of the raw data to ensure accuracy and completeness of the data.
   i) Deduplication: Removing duplicate data to avoid double accounting.
   ii) Denoising: Removing noise or outliers from the data to reduce errors and improve data quality. Common methods for removing outliers include the z-score method, the 3σ (3-sigma) rule, and the boxplot method.
      - The z-score method calculates the z-score for each data point and removes those that have a z-score greater than a certain threshold (typically 3 or 4). This method identifies outliers based on how far a data point deviates from the mean.
      - The 3σ rule identifies outliers by considering the standard deviation of the data. According to this rule, data points that are more than 3 standard deviations away from the mean are considered outliers.
      - The boxplot method uses the interquartile range (IQR) to identify outliers. It constructs a box around the middle 50% of the data and marks any data points that fall above or below a certain range as outliers. This method is particularly useful for detecting outliers in skewed datasets.

b) Interpolation: Filling missing data with interpolation methods for subsequent data fusion and analysis. Common methods including linear interpolation (estimating missing values by drawing a straight line between the closest known values on either side of the gap and assigning intermediate values) or spline interpolation (using mathematical functions, e.g., cubic splines, to estimate missing values based on the overall trend of the data).

c) Normalization: Data normalization is the process of standardizing the data from different sources to ensure comparability of the data.

By going through these steps, the accuracy, completeness, and comparability of the data can be ensured, providing a reliable foundation for subsequent integration of urban GHG data into a unified data set.

9 GHG emission data fusion

The method of fusing accurate regional emission data and high-resolution active data, including data alignment, data association, and data estimation, which is shown in Figure 3.

– Data alignment: This involves aligning the regional emission data and the high-resolution active data to ensure that they can be properly merged. This is done by matching the data formats, units, and time periods of the two datasets.

– Data association: In order to accurately merge the two datasets, it is necessary to associate the high-resolution active data with the corresponding regions in the emission data. This is done by using geographic information system (GIS) data and other spatial analysis tools to match the location of the high-resolution active data with the corresponding regions in the emission data.

– Data interpolation: Once the two datasets are aligned and associated, data interpolation techniques are used to fill in any missing data or gaps in the datasets. This involves using statistical methods, such as regression analysis, to estimate missing data based on the available data and other relevant factors.

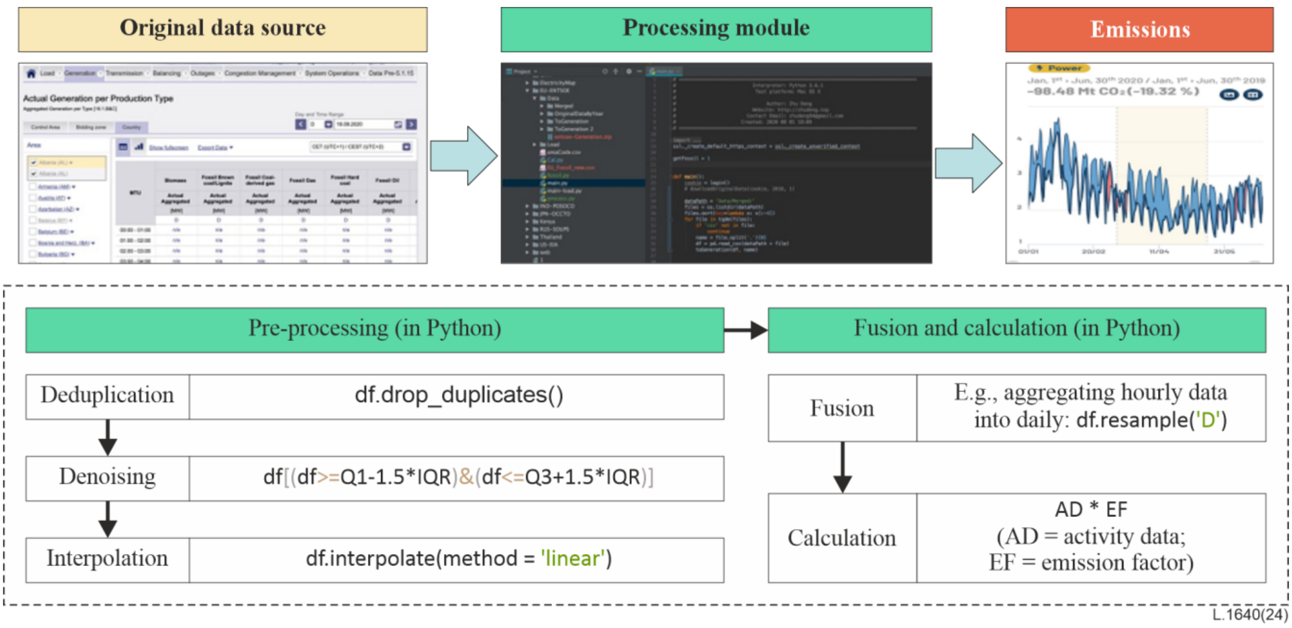


Figure 3 – A simplified workflow of data processing and fusion

10 GHG emission calculation

a) Data collection and processing: The collection of GHG emission data in cities can be achieved through various technical means, such as using sensors, traffic flow monitoring, satellite remote sensing, etc. The collected data needs to be cleaned and processed for subsequent computation and analysis.

b) GHG emission calculation model: To achieve near-real-time GHG emission calculation, an appropriate model needs to be established. The model should consider the characteristics and actual situation of the city, including traffic conditions, industrial and energy consumption, etc., to more accurately estimate GHG emissions:

   i) ICT goods, networks and services GHG emission should be accounted according to [ITU-T L.1410].

   ii) ICT technology in organization GHG emission should be accounted according to [ITU-T L.1420].

   ii) ICT GHG and energy project emission should be accounted according to [ITU-T L.1430]

   iv) ICT at city level GHG emission should be accounted according to [ITU-T L.1440].

   v) ICT sector GHG emission should be accounted according to [ITU-T L.1450].

c) Support of cloud computing platform: GHG emission calculation requires a large amount of computing resources, so a cloud computing platform can be used to achieve this. Cloud computing platforms can provide high-performance computing, large-scale data processing and storage functions, thus achieving high efficiency and low cost of GHG emission calculation.

d) Visualization and analysis: Data analysis can analyse and explain the monitoring results of GHG emissions in cities from multiple perspectives, thus better understanding the situation of GHG emissions in cities. Data analysis can use various methods, such as statistical analysis, visualization analysis, machine learning analysis, etc. The results of visualization analysis can be presented to users intuitively through charts, maps, reports, etc., thus better supporting city management and decision-making. The example of visualization analysis of GHG emissions for city is shown in Appendix II.

11 Attribution analysis of GHG emission data and optimization strategy for sustainable development of city

11.1 Emission sources analysis and attribution analysis

Statistical analysis and machine learning methods achieve the recognition and classification of GHG emissions sources. Classification of the emissions sources, meaning the assigning of the properties for the studied GHG emissions to one of the sources. Recognition of the emissions sources, meaning the establishing of the affiliation for GHG emissions to one of the disjoint known sources.

Quantitative attribution analysis can serve as a proxy for similar events occurring at different temporal and spatial scales, which should consist of the following components:

– To assess the emission levels using historical activity levels as benchmarks and identify the hotpots of emission increases.

– To explore the decoupling relationship between activity levels and carbon emissions.

– To investigate influencing factors and facility-based contributions using multiplicative decomposition analysis and the related attribution analysis.

11.2 Optimization strategy for sustainable development of city

An optimization strategy should be designed and implemented to reduce emissions. The technology optimization methods consist of the following components:

– Clean power promotion, including reduction of end-use fossil fuel through fuel substitution and electrification, renewable energy promotion, building zero-carbon electric power systems.

– Energy efficiency improvement through structural adjustment, product substitution, process re-engineering, energy saving and behavioural change from the consumer.

– Carbon negative technologies.

– Non-CO2 greenhouse gas emissions reduction technologies.

The optimization strategy should be reviewed periodically to reflect changes in the mitigation strategy, challenges, and achievements. In the case of recertification, previous GHG emissions reduction work strategies should be reviewed to examine whether previous goals and objectives have been met.

Appendix I

Example of monitoring city-level CO_2 emissions from ground transportation in China

(This appendix does not form an integral part of this Recommendation.)

I.1 General procedure of the example

This example discusses in the case of a lack of high-frequency fuel consumption statistics in urban transportation, how to establish a congestion index-traffic flow model by using only road traffic flow data during certain periods in the city, combined with the near-real-time congestion index of the city's road network. Based on simulated near-real-time traffic flow data, the fuel consumption and greenhouse gas emissions of the transportation department are estimated (Figure I.1). In this example, we established a road traffic emission model for Beijing, and the road traffic flow data during certain periods comes from real research and statistics on roads, while the road congestion index of the entire road network comes from digital map vendors. We will apply the model constructed in this example to 100 cities in China to estimate the near-real-time changes in traffic greenhouse gas emissions in these cities.

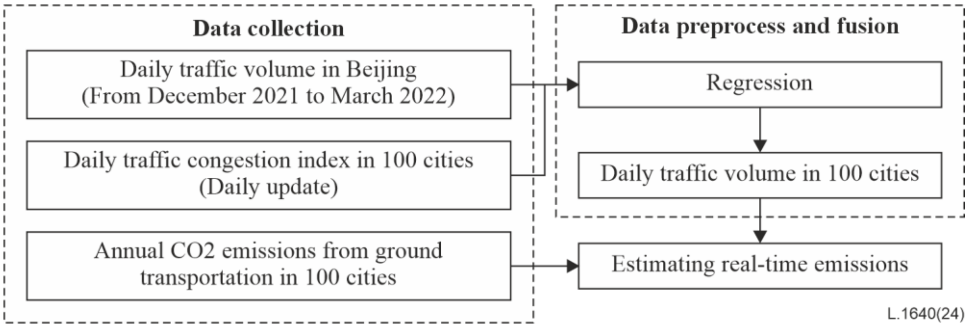


Figure I.1 – Flowchart for estimating real-time traffic carbon emissions in cities

I.2 Example of collecting city-level activity data

Table I.1 shows the types of raw data collected for estimating city-level ground transportation CO2 emissions in China.

Table I.1 – Raw data used for estimating near-real-time daily city-level ground transportation CO2 emissions in China

Data	Description
Daily traffic flow	Daily traffic flow for all roads in Beijing from December 26, 2021 to March 29, 2022
Daily traffic congestion index	The index is updated daily and covers 100 cities nationwide, as it represents the ratio of the actual trip time to the trip time in uncongested conditions.
Annual CO2 emissions	Total ground transportation CO2 emissions in 100 cities nationwide for the year 2019

I.3 Example for data process and data fusion

This section aimed to estimate near-real-time daily emissions from ground transportation by utilizing the daily traffic congestion index as a proxy for the daily on-road car flux. To this end, the primary objective of this section was to establish the relationship between the daily traffic congestion index and the daily traffic flow to complete the daily traffic flow data for 100 cities. The daily traffic congestion index represented the ratio of the actual trip time to the trip time in uncongested conditions. A daily traffic congestion index with a value of 1 did not necessarily indicate zero emissions but rather indicated that traffic flow was fluid or 'normal'. To estimate the lower threshold of emissions, daily traffic flow data for all roads in Beijing from December 26, 2021, to March 29, 2022, was utilized, and the same was defined as the mean number of passing vehicles recorded by the camera within one hour.

A sigmoid function with regression parameters α, β, γ, and λ was utilized to represent the relationship between the daily traffic congestion index X and the daily traffic flow Q, as shown in Equation (I.1) [b-Da]:

$$Q = \alpha + \frac{\beta[100(X-1)]^{\gamma}}{\lambda^{\gamma}+[100(X-1)]^{\gamma}} \tag{I.1}$$

The model was fitted using the least squares method, and the fitting results were presented in Table I.2. The flow model was found to be close to the real traffic flow in Beijing. Although traffic characteristics vary among cities, it was assumed that daily traffic flow for other cities follows a similar relationship to the fitting models in Beijing (Equation I.1), and this model was applied to the other 99 cities. While the use of city-specific regression models would improve accuracy, it is believed that this approach is a reasonable approximation of Beijing's traffic condition and is known to be a good representation of the country's average due to its high diversity in road types.

Table I.2 – Regression parameters of the sigmoid function of Equation I.1 that describe the relationship between traffic flow (Q) and congestion and delays indicators (X)

Regression parameter	Value
a	11089.30
β	23460.82
λ	1.40
γ	17.93

I.4 Example for estimating daily GHG emissions in near-real-time

Assuming a linear relationship between daily CO_2 emissions and daily traffic flow, the daily CO_2 emissions from ground transportation are established based on annual CO_2 emissions and daily traffic flow as the distribution coefficient. Equation (I.2) shows the daily ground transportation emissions $E_{c,d}$ for a specific city c in day d: [b-Da], [b-Zhu 1].

$$E_{c,d} = Q_{c,d} \times \frac{E_{c,y}}{\sum_d Q_{c,d}} \tag{I.2}$$

where $E_{c,d}$ is the ground transportation emissions for city c in day d, $E_{c,y}$ is the ground transportation emissions for city c in year y, and $Q_{c,d}$ is traffic flow for city c in day d.

Equation (I.3) establishes the daily CO_2 emission model of ground transportation for the 100 cities in China, with daily ground transportation emissions $E_{c,d}$ in day d given by Equation (I.3) [b-Da], [b-Zhu 1]:

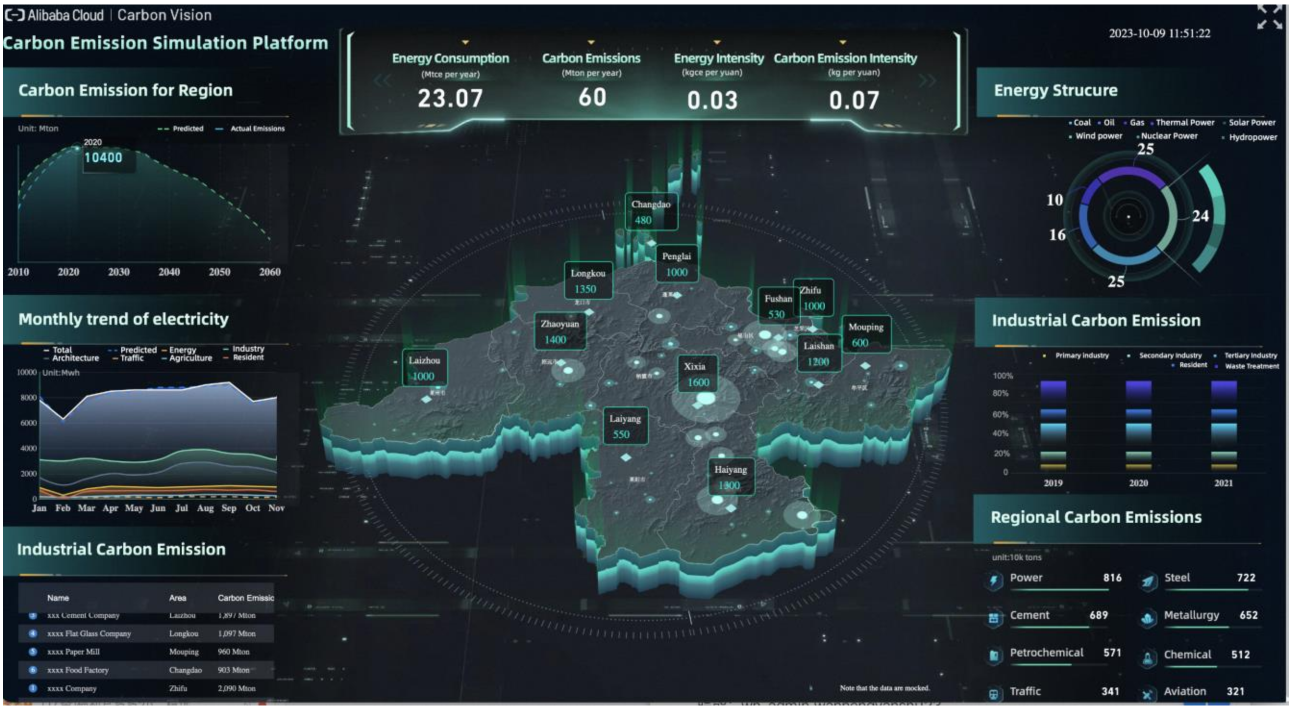
$$E_{c,d} = Q_{c,d} \times \frac{E_{c,2019}}{\sum_d Q_{c,d}} \tag{I.3}$$

where $E_{c,d}$ is the ground transportation emissions for city c in day d, $E_{c,2019}$ is the ground transportation emissions for city c in 2019, and $Q_{c,d}$ is traffic flow for city c in day d.

Appendix II

Alibaba Cloud's "Carbon Vision" platform showing city near-real-time GHG emissions (mocked data)

This appendix presents an example of visualization analysis of GHG emissions for city, including the functions of monitoring energy consumption, energy intensity as well as GHG emission from different locations of the city. Additionally, it can also show GHG emission trends and the energy resources composition of the city.



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