Information requirements over the asset lifecycle to include carbon into digital twin: A UK highway example

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Abstract

Digital twin (DT) has the potential to facilitate the reduction of carbon emissions over asset lifecycle, which is a critical target that should be instructed by real-time data. However, the trustworthy carbon data to feed into DT to support environmental impact assessment, identification of hotspots, and carbon reduction progress monitoring is largely missing in literature and practice due to the lack of a clear asset carbon information requirements (ACIR). This paper sets out to develop the ACIR for the collection of fine-granular carbon data for highway DT by reviewing relevant standards, industry guidelines, and tools and engagement with industry experts through a design-thinking workshop. A total of 74 ACIR are added to the ISO 19650 asset information requirements, among which 38 are sustainability or carbon directed and 12 are in the technical aspects. These ACIR provide a foundation for developing a carbon DT for highway assets that can facilitate real-time sustainability-orientated decision making. Future research directions to facilitate the completeness and the implementation of the ACIR are recommended.

Keywords: Carbon data, asset information requirements, digital twin, highway asset

1 Introduction

Carbon data is the information related to carbon emissions that can help us to understand the carbon footprint of various activities, processes, products, or organizations. While carbon data is crucial to assess the environmental impacts, identify areas for improvement, and monitor the performance/progress in reducing carbon emission for net-zero targets, there is surprisingly no clear definition and information requirement to capture trustworthy carbon data with appropriate granularity to meet the increasing demand of fine-granular carbon analysis (Martin et al., 2014; Yu et al., 2016). Without clear information requirements, it is difficult to ensure carbon data is accurately and consistently collected, measured, and reported across different sources, activities, or organizations.

In light of mounting regulatory and financial demands, coupled with stricter standards, the construction and infrastructure industry has been actively seeking innovative practices and tools to collect carbon data. However, without orchestrated data requirements, various schemes and tools are using bespoke data protocols, formats, and processes, facing challenges in data availability, data consistency, data interoperability, and data security, which creates issues over trustworthiness (Xu & MacAskill, 2023). Meanwhile, a digital twin (DT), a purpose-driven dynamic digital replica of a physical asset, process, system, or product (Moyne et al., 2020), is a trending technology that integrates data from different dimensions together in one platform to support data-informed decision making. There is huge potential to embed carbon data in DT platforms for carbon management. However, DT platforms for physical infrastructure largely remain in an inceptive phase of development, where carbon is not typically included in core information requirements, except some recent efforts to develop a construction carbon emission management ontology integrating diverse carbon emission data sources (Lu et al., 2024).

This paper sets out to develop information requirements (IR) over the asset lifecycle for the collection of fine-granular carbon data by conducting a review on documents relating to carbon data. It will map carbon data for a DT as one of its essential elements. The aim is to clarify the information requirements to include carbon in DT. For clarity and ease of explanation, this study will use highway assets as the research object. It is also because information requirements for highway asset DT over its lifecycle is less studied compared to buildings which can inform the carbon DT for highways.

The rest of this paper is organized as follows: Section 2 provides the background by reviewing asset information requirements (AIR) for a DT, and carbon data sources, integration, and trustworthiness issues. Section 3 reports the research methodology for developing the asset carbon information requirements (ACIR) and Section 4 proposes the ACIR for highway assets over its lifecycle. Section 5 discusses the findings before conclusions are drawn in Section 6.

2 Asset information requirements and carbon data

2.1 Asset information requirements for digital twin

Three key types of information requirements in the management of built environment assets are: Organizational Information Requirements (OIR), AIR, and Exchange Information Requirements (EIR). OIR are high-level information needs defined by an organization. AIR detail the specific information needed about individual assets to support their effective management throughout their lifecycle. EIR specify the information to be exchanged between project stakeholders at various stages of an asset's lifecycle. Outlined in standards like ISO 19650, traditional AIR focus on fundamental aspects such as: basic identifiers and classifications for each asset, location and spatial data essential for planning and operations, historical and scheduled maintenance tasks, performance characteristics, and operational limits, standards, procedures, hazardous content details (ISO, 2020). These AIR provide a foundation for managing asset performance, condition, and maintenance needs.

Developing AIR involves a detailed and structured approach that aligns with the organization's strategic objectives (i.e., OIR) and supports effective lifecycle asset management. A DT is a digitalized platform integrating geometric and semantic information of assets (Li et al., 2024). AIR are significant for DT-enabled engineering asset management (Johnson et al., 2021; Li et al., 2024). If AIR are not collected to support organizational requirements, organizational performance of capital investment, risk management, operation and maintenance, and ultimately productivity will be restricted (Heaton et al., 2019). While carbon management is becoming a significant feature in organizational decision-making, there is no systematic ACIR for organizations to collect and exchange carbon data between stakeholders (Carvalho & da Silva, 2021). This gap restricts efforts reduce and monitor carbon emissions.

2.2 Carbon data

Generally, for carbon management of infrastructure the required data encompasses activity data and emission factor data. Researchers predominantly rely on pre-existing databases to obtain emission factor data. There are over fifty databases, both commercial and non-commercial, at different completeness and granularity levels (Liu et al., 2022). Notably, the One Click LCA database stands out as one of the largest repositories of environmental data pertinent to construction endeavors worldwide. It encompasses over 150,000 meticulously reviewed, verified, curated, and integrated data points sourced from a diverse array of public and private outlets. Additionally, the EcoInvent database is another widely referenced repository, boasting an extensive compilation of more than 18,000 data points derived from companies, industrial associations, and research institutes, covering a broad spectrum of sectors at both global and regional scales (Li et al., 2023).

Meanwhile, activity data is derived from diverse origins. Researchers often resort to literature, drawings or models, or on-site surveys to acquire the necessary activity data.

Literature can provide empirical data. Drawings or models supply geometrical and some semantic data about the infrastructure. However, since such models are rarely developed with environmental assessment as the primary goal, Nahangi et al., (2021) suggested to change the scope and detail of the models before they are used for effective embodied GHG assessment. Where data is sourced from onsite surveys, it is usually collected from the field through onsite observations and interviews with site professionals (Krezo et al., 2016). Similar survey methods were also used to measure household road transport use (Gupta, 2014) and to collect fuel consumptions such as machine diesel recordings (Krezo et al., 2018).

Many scholarly studies are interested in how to integrate data from diverse sources with disparate data formats. Notably, a prominent focus in contemporary research is the integration of BIM and LCA data. BIM serves as a repository of invaluable information, encompassing geometrical and physical characteristics, bill of quantities (BoQ), material specifications, and other relevant details concerning infrastructure components and materials. The integration of BIM models with LCA tools emerges as a critical juncture to ensure the seamless extraction of relevant data from BIM models for input into LCA tools (Tam et al., 2022). In the synthesis presented by Tam et al. (2022), six distinct types of data exchange between BIM models and LCA data have been identified: (1) exporting BoQ into Excel, (2) exporting BoQ into dedicated LCA tool, (3) adopting LCA plugin for BIM software, (4) using IFC (industry foundation classes) format of BIM models for data transfer, (5) using VPL (visual programming languages) for environmental impact evaluation, and (6) including LCA information directly in BIM objects.

The trustworthiness of carbon data has emerged as a significant focus within academic research and industry. Various data-related issues, including availability, quality, security, and compatibility, collectively fall under the umbrella of data trustworthiness (Xu & MacAskill, 2023). Researchers have identified specific challenges related to data collection, transparency, and reliability. The labor-intensive nature and deficiencies in the data collection process for back-calculating total emissions was emphasized as a blocker to integrate carbon emissions into road project tendering and procurement (Anthonissen et al., 2015). The required manual efforts raised questions about their associated shortcomings in feasibility and efficiency.

2.3 Research gap

This collective body of research highlights the multifaceted challenges associated with ensuring the trustworthiness of carbon data from its sources and integration. There is a fundamental lack of systematic understanding of what carbon-related information should be collected to support the efficient carbon management of assets throughout their life (Heaton et al., 2019). This accentuates the critical necessity to address issues encompassing asset carbon accounting methods, data transparency, data reliability, and data consistency by providing a clear carbon information requirement. A pathway towards better informed decision-making for carbon emissions management requires appropriate, relevant, and effective AIR, supported by clear definitions with regards to what data should be collected at what time by whom.

This paper aims to answer one research question: What are the AIR to include carbon in DT for more intelligent carbon management? This paper sets out to develop an ACIR for the collection of fine-granular carbon data by taking forward the directions in academic literature and conducting AIR development following ISO 19650-3. It aims to help asset owners to identify the ACIR over the asset lifecycle to include fine-granularity, dynamic, specific carbon data in asset DT for data-informed intelligent carbon management.

3 Research methodology

The development of information requirements follows the principles, processes, and methodologies in ISO 19650 series, which is a set of international standards on "Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM) – Information management using building information modelling". The assumptions of this study are that: (1) asset owners follow these ISO 19650 standards in their information management; (2) asset owners have clear OIR on carbon management; (3) asset owners have a predefined process to develop asset functions, systems, and products within a classification system, such that there is no need to develop another classification system when developing the ACIR.

OIR and AIR from the ISO 19650 standards as the overall framework of asset information requirements and the UK National Highways asset data management manual (ADMM) as the contextual guidance for highway assets are the original data sources for developing the ACIR for highway assets. Carbon related items from both sources are identified first and combined to align under the ADMM classification framework for highway asset functions, systems, and assets. Then asset carbon information requirements (ACIR) of these functions, systems, and assets are further identified based on existing carbon relevant technical guidelines, codes, regulations, specifications, and tools in the highway sector. To ensure these identified ACIR from existing literature are comprehensive and meet the practical requirements of carbon management, a design-thinking workshop was conducted to identify ACIR needed in practice. The ACIR in practice is checked against the ACIR in literature to form an updated and comprehensive ACIR. Figure 1 illustrates the workflow of the carbon information requirements development, with adjustment to the workflow developed by Heaton et al., (2019).

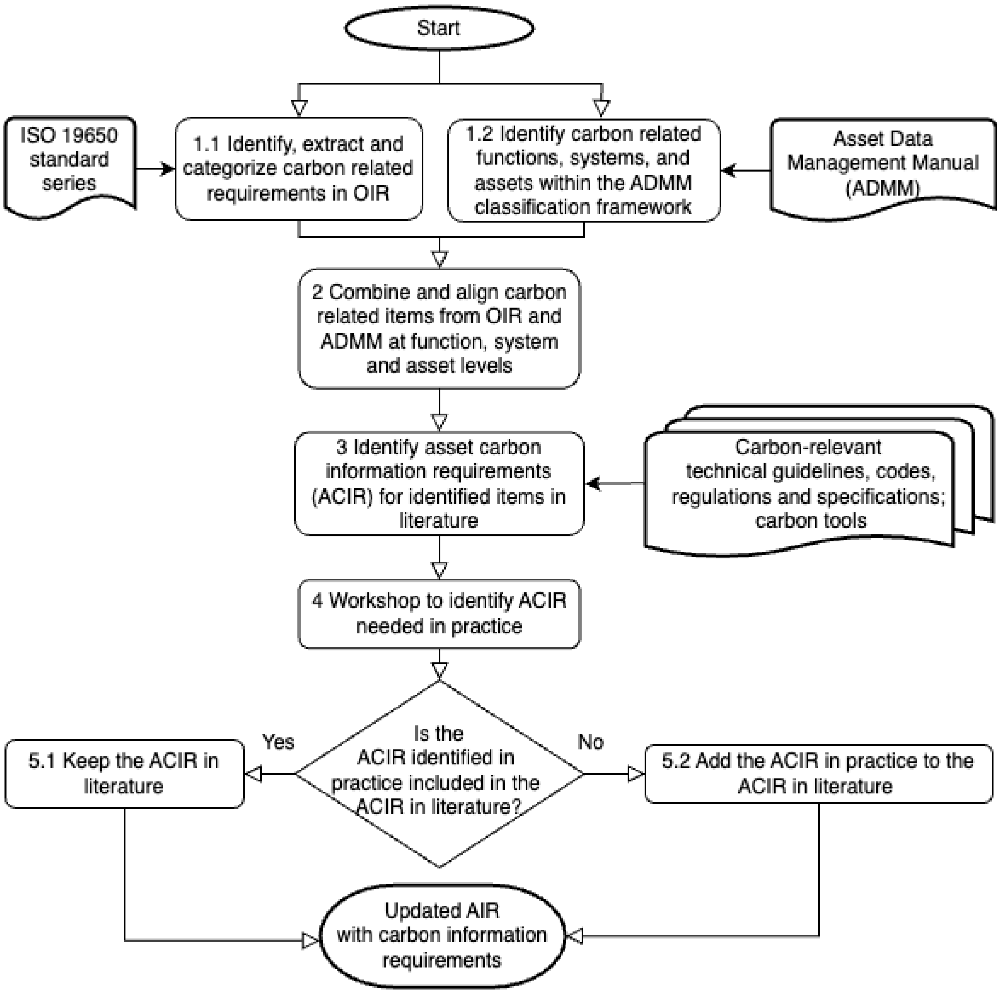

Figure 1. Carbon information requirement development workflow (Heaton et al., 2019)

This research adopted a mixed-method research design. The ISO 19650 standard, ADMM, and carbon-relevant literature were reviewed to identify the ACIR. A design-thinking workshop was organized to identify the ACIR needed in practice. Sixty-two industry experts from 33 companies across the UK highway value chain covering asset owner and manager, designer, contractor, product/material supplier participated in the one-day in-person workshop, with another 5 academics from 2 research institutes. In the workshop, with the guidance of professional facilitators, all the participants were asked to work in groups to list the data needed for carbon management and to prioritize them. Then the listed ACIR and their frequencies are summarized.

4 Proposed asset carbon information requirements (ACIR)

The scope of this study is carbon information for highway asset over its lifecycle in the UK context. Carbon relevant items in the function and system levels are identified and displayed in Figure 2. Figure 2 does not cover all assets but gives an example of how bridge and large culvert structures are further broken down into smaller elements. Carbon emissions are generated in the production, transportation, construction and operation of different functions (middle part of Figure 2) and their assets (lower part of Figure 2). Data related to different functions are collected and stored in different systems as listed at the upper part of Figure 2. This classification framework provides a reference of what items should be considered when requiring carbon information. Based on the identified items, the ACIR is developed from the perspective of the asset owner/developer with consideration of its value chain stakeholders.

To better incorporate IRs with the requirements of DT, the principles of developing the ACIR (Moyne et al., 2020) include:

Availability: the required information should be measurable and quantifiable with existing techniques or future technologies

Consistency: the information included in the ACIR should be reusable and scalable in different highway assets to support DT solutions across entire highway asset ecosystem;

Quality: considering the quality requirement in DT maintenance and the trend toward being fully automated across the entire DT lifecycle under common DT definition, taxonomy and other mechanisms for collaboration;

Interoperability: multiple instances of the same ACIR class must be allowed to interact in a coordinated fashion, integration of and coordination between instances of different ACIR classes and between carbon and non-carbon components to support structured and automated integration of evolving analytics;

Security: addressing security requirements in information storage and exchange.

Following the workflow in Figure 1 and the five principles as listed above, a set of ACIR that includes carbon-relevant information both in current literature and identified as requirements in practice is summarized, as listed in Table 1. The new information requirements in managerial, technical, commercial and financial aspects are added to the existing ones listed in ISO 19650-3. A new carbon-specific aspect is also added, as listed in the last column of Table 1. The current IRs are relatively general and high-level because they are for generic building information models, but the new IRs are specified for the highway assets and are more sustainability (particularly carbon) focused. Together, they form a more comprehensive AIR by creating ACIR for data-driven carbon management. It should be noted that this list is not inclusive to all relevant AIR that should be considered but the ones that are identified from literature and from the workshop; there are more AIR that needs to be included for the collection of complete information, which is the next step of research through case study and focus group.

The current IRs from the managerial aspect provide a framework of the physical and operational characteristics of assets with unique identifiers, locations, spatial data, and maintenance records. From the technical angle, current IRs provide foundational design, engineering, and operational parameters, as well as the interdependencies between assets. Current commercial IRs describe asset functions, vendor, performance indicators, asset conditions and criticality. Financially, current IR focus on whole life costs, operating costs, downtime impacts, and replacement values.

There are a total of 74 newly added IR items added, among which 38 are carbon directed with some about wider sustainability and 12 are in the technical aspects. For the new technical IRs, design information relating to green, biodiversity, material specifics, disassembly, as well as actual detailed data in construction, operation, maintenance, and traffic movement are desired. For the managerial aspect, information relating to operation and maintenance (e.g., repair, rework, replacement), use (traffic demand, asset life expectancy), and sustainability management (sustainability business model, sustainability score/index, biodiversity net gain) are added. Financially, cost details, especially on material and energy/fuel are required for cost saving comparisons and lifecycle costs to customers measurement, carbon and biodiversity cost are included. Commercial IRs to measure performance, profit, and customer experiences are added.

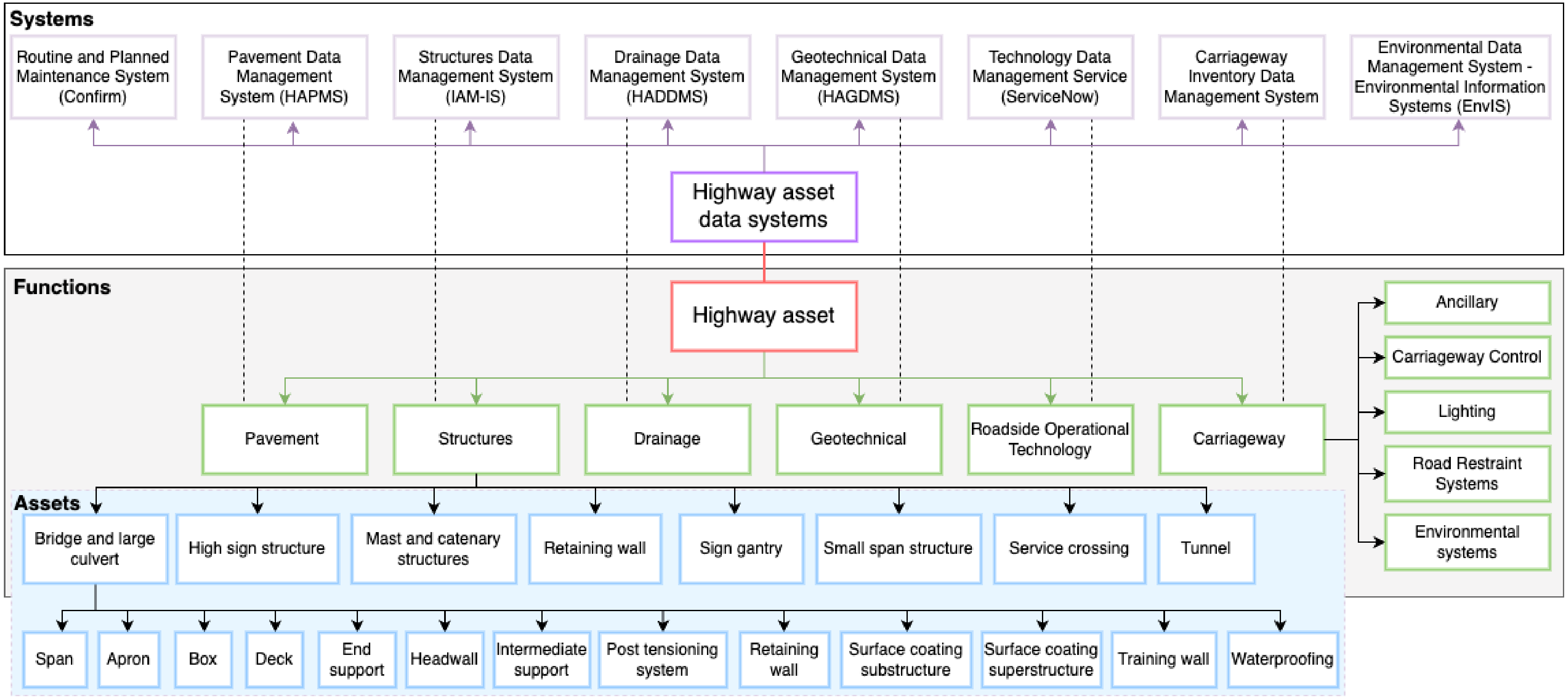

Figure 2. Classification of the carbon-relevant systems, functions, and assets (non-inclusive example)

Table 1. Asset information requirements of highway assets over its lifecycle with carbon information included

Managerial	Technical	Commercial	Financial	Sustainability/Carbon
Current IR 1. unique asset identifiers 2. locations of the assets, possibly using spatial referencing or geographical information systems 3. spatial data relating to assets, for example pavement areas, room sizes 4. warranties and guarantee periods 5. access planning and work schedules 6. historical record of proactive and reactive maintenance tasks performed 7. future schedule of maintenance and inspection tasks including details of overdue tasks, and including details of the maintenance organization and details of qualifications/certifications required to carry out each task 8. asset related standards, process(es) and procedure(s) 9. the presence of any hazardous contents or waste 10. details of asset destination at end of current life 11. details of historical asset failures, causes and consequences (if known) **New IR** 12. rate of road repair 13. frequency of reworking maintenance 14. frequency of expected replacement - durability 15. result from resting regines (durability, structural performance) 16. asset life expectancy 17. traffic demand/survey 18. sustainability business model 19. sustainability score/index 20. biodiversity net gain	**Current IR** 1. engineering data and design parameters 2. details of technical dependencies and interdependencies of assets 3. commissioning dates and data 4. operational data including performance characteristics and design limits **New IR** 5. Design of green space, BREEAM score 6. design information of materials 7. design information of biodiversity 8. disassembly design 9. continuous monitoring of data in operation, maintenance, and traffic movements 10. method of construction 11. actual use of materials on schemes 12. resources logistics 13. accurate new or maintenance project data 14. capital replacement, maintenance data 15. EV charging facility performance 16. circularity and recyclability technical data	**Current IR** 1. descriptions of assets and the asset systems they serve 2. functions of assets, including any interdependencies to the activities that require them 3. vendor data (details of the organization that supplied the asset) including asset lead time 4. the condition and duty of assets including intensity of use 5. key performance indicators 6. condition and performance targets or standards 7. criteria of non-conformance and the actions to be taken 8. the criticality of assets and spaces to the organization 9. identities and levels of spares held, inter-changeability, specifications, and storage locations **New IR** 10. wins (what % bids won / competitiveness) 11. profit 12. material / process availabilities 13. customer experience improvement 15. energy/fuel cost 16. performance against standards and specifications	**Current IR** 1. whole life costs of asset deployment including cost of historical and planned maintenance tasks 2. operating costs 3. downtime impact 4. current asset replacement value 5. original purchase/leasing costs **New IR** 6. cost savings (option 1/option 2 comparison) 7. lifecycle cost to customers 8. design costs, construction costs, disposal, replacement + maintenance costs 9. cost of all materials, including waste, transport 10.cost of carbon tax / sequestration /offsets /credits 11. ROI (return of interest) 12. biodiversity payments 13. bond rating/credit rating (investor financial health, operating company business resilience, supplier business resilience)	**New IR** 1. carbon baseline 2. material carbon baseline 3. actual carbon over the lifespan of the asset 4. Scope 1, 2, 3 emissions 5. design carbon 6. construction carbon 7. maintenance carbon 8. operation carbon 9. end user carbon 10. carbon in transportation 11. carbon in placement 12. carbon in site management 13. embodied carbon 14. operational carbon 15. quantities of material 16. quantities of energy/fuel 17. material transport distance, methods, supply chain map 18. material reuse (reuse as % in total) 19. % recycled material 20. CO_2e/m^3 concrete for m2 construction 21. CO_2e/tonnes cement 22. quantities of waste 23. reduced waste 24. whole life carbon avoided 25. reduction of CO_2e per m^2/km 26. carbon absorption 27. captured carbon (or draw down) 28. net positive data 29. intervention/ reduction in cost%carbon (route comparison, old & new road) 30. updated carbon database/library with carbon emission factor for all raw materials inputs, activities 31. material passports/ Environmental Product Declarations 32. waste/efficiency factors 33. carbon intensity per user per km 34. carbon per km pre/post intervention 35. carbon per vehicle pre/post intervention 36. user journey distance 37. user journey start & end location 38. water consumption

The direct sustainability/carbon IRs introduce a broad range of metrics to capture carbon emissions across the asset lifecycle, including carbon baselines, Scope 1, 2, and 3 emissions, and specific carbon metrics for design, construction, maintenance, operation, and end-of-life stages. It covers material carbon, operational carbon, waste reduction, and circularity data. Specifically, material carbon related information and the carbon emissions from different lifecycle stages in different activities are the mostly required. Some of the IRs can relate to others or share some overlaps, for example, material carbon baseline would need material emission factors from material passports or environmental product declarations (EPD) and the quantities of materials which can also help measure the quantities of waste, material reuse, and material recycle. Embodied carbon can be measured by adding emissions from design, construction, maintenance, asset operation emissions. End user emissions is part of operational carbon that related to user journey distance which can be measured from the start and end location, and it can be used to measure carbon intensity per use per km. When carbon baseline and actual lifecycle carbon are measured, they can be used to calculate whole life carbon emission avoided which can further be used to measure the reduction of CO_2e per m^2/km, and to compare the CO_2e per/km or CO_2e per/vehicle before and after the development or renewal of a new highway asset or the introduction of new technologies. The relationships between the carbon emission measurement relevant IRs are illustrated in Figure 3.

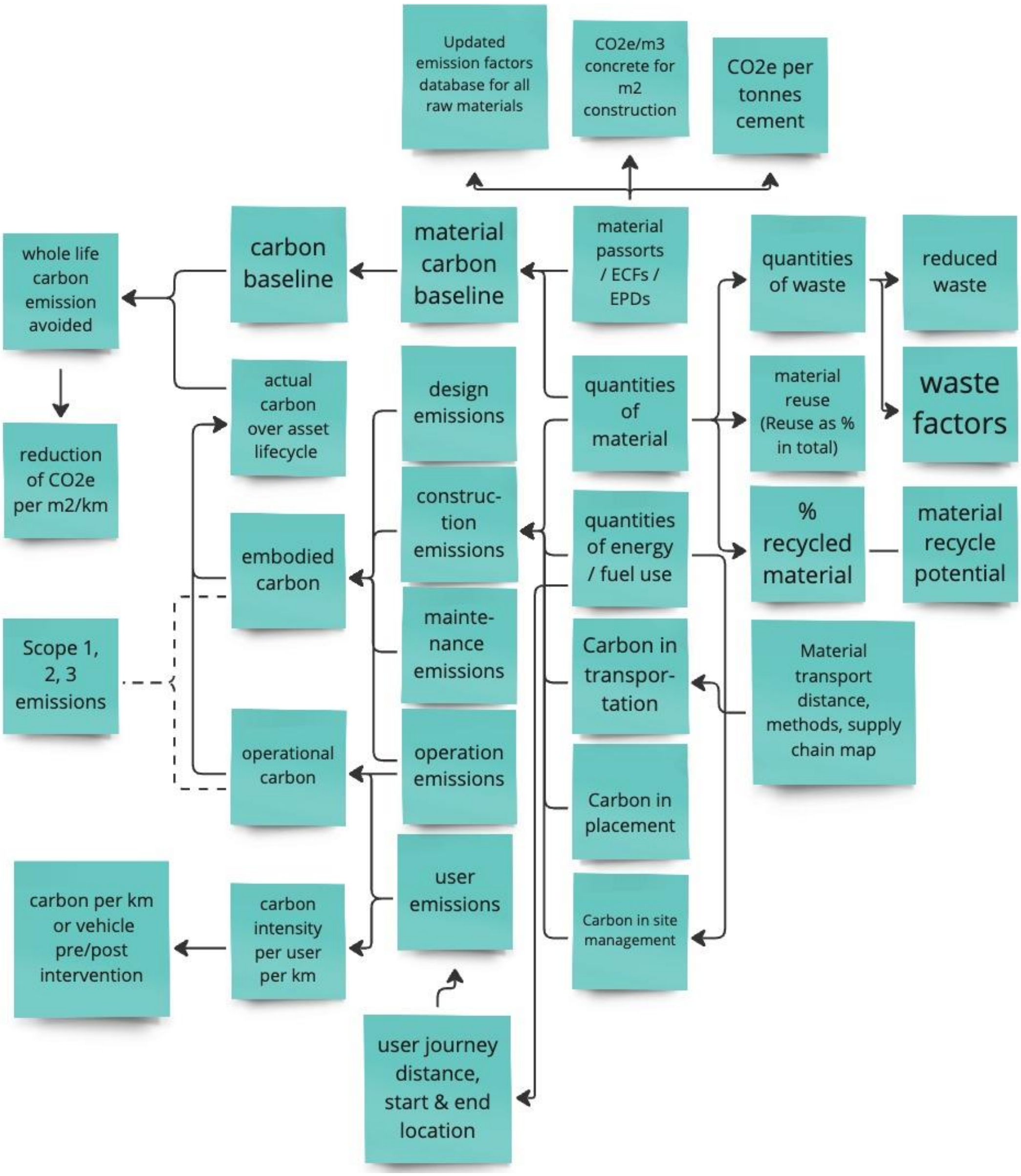

Figure 3. Relationships of carbon emission measurement relevant IRs

Also, some of the IR are quite general and abstractive, which require more priori data to support their calculation. Follow-up research to break them down into the measurable granularity will be conducted with case studies and focus group with practical professionals.

5 Discussions

The ACIR provides a foundation for developing a sustainability/carbon DT for highway assets. Such DT can enhance environmental sustainability in three aspects:

1. Holistic carbon management: Detailed carbon IRs allow for comprehensive carbon management. The DT can track emissions across all lifecycle stages and activities, supporting strategies for carbon reduction, offsets, and achieving net-zero emissions.
2. Resource-efficient operation and maintenance: Incorporating traffic demand, asset performance data, material and fuel carbon factors into a DT enables accurate resource-efficient operation and maintenance by optimizing transportation services while considering low-carbon materials, material recyclability, reusability and circularity, operation and maintenance methods.
3. Real-time decision-making for sustainability: Real-time monitoring of wider sustainability (e.g. biodiversity, water use) and more specifical carbon data and integrating them in a DT supports sustainability-driven decision-making for both asset owners and users.

However, how to implement the ACIR in developing DT is not covered in this paper. A more detailed breakdown of the ACIRs, mapping them with the properties of objects in DT, developing a standardized data scheme for the new ACIRs, and developing exchange information requirements (EIR) for value chain stakeholders to share carbon-relevant information are potential future research directions.

6 Conclusions

This paper set out to develop ACIR over the highway asset lifecycle for the collection of fine-granular carbon data by taking forward the directions in academic literature and conducting review on documents relating to carbon data. It added 38 sustainability related AIR, especially carbon relevant IR, in the DT as one of its essential elements. It contributed to the enrichment of DT. The integration of detailed managerial, technical, commercial, financial, and sustainability/carbon-specific IRs into a DT framework allows for data-driven decision-making toward more comprehensive and sustainable asset management. The focus on sustainability and carbon management helps organizations meet regulatory requirements and sustainability goals while maximizing their management performance, technology advancement, commercial and financial performances.

Future research should focus on completing the ACIR to identify and include possible missed ACIR from literature and workshop, breaking down the proposed ACIR with better data granularity, mapping them with the properties of DT objects, developing a standardized data scheme for the implementation of the ACIR, and developing EIR for data sharing among value chain stakeholders of highway assets across their lifecycle. This will facilitate consistency and comparability across different organizations and projects during the implementation of the ACIR.

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