How good are the best practices in carbon reduction? UK highway sector case studies

Jinying Xu[1] and Kristen MacAskill[1]

[1]Department of Engineering, University of Cambridge, United Kingdom.
jx314@cam.ac.uk, kam71@cam.ac.uk

Abstract –

To achieve net-zero targets in the transportation infrastructure sector, cost-effective carbon reduction measures are essential. Despite increasing efforts to explore such measures, their cost-effectiveness remains underreported and insufficiently studied. A database of best practices with 1,046 entries from UK National Highways is extracted to investigate the cost-effectiveness of its carbon reduction strategies. The analysis identifies "Project and programme management" as the primary focus area, with the construction stage being the most emphasized stage. Four "Carbon Quick Wins" approaches and the carbon reduction hierarchy (Avoid-Reduce-Switch) are the main strategies employed. Although "Avoid" has the greatest reduction impact and the highest hierarchy in decision-making, it is less frequently reported in the register of best practices than "Reduce" and "Switch" to low carbon material and energy. Using data mining techniques, the cost and carbon reduction data are extracted to evaluate the cost-effectiveness of carbon reduction using marginal abatement cost (MAC) indicator. The MACs of eighteen cases demonstrate significant variations, complicating the performance evaluation of these best practices. The study reveals a lack of data in most practices to measure the cost-effectiveness of carbon reduction initiatives. Even with available data, its granularity is rough, potentially influencing the selection of appropriate approaches. Standardized methods to measure the cost and wider impact of carbon reduction initiatives are recommended for future research along with data reporting policies.

Keywords –

Highway infrastructure; Carbon reduction; Carbon-cost effectiveness; Best practices; UK

1 Introduction

The transportation sector, particularly highways, is a significant contributor to carbon emissions, a primary driver of climate change [1]. In response, the transportation sector in different countries has implemented various strategies aimed at reducing these emissions to meet both national and international environmental targets. For example, UK National Highways (NH) aims to achieve net-zero corporate emissions by 2030, net-zero maintenance and construction emissions by 2040, and net-zero road user emissions by 2050 [2].Their carbon reduction strategies include avoiding high-emission activities and materials; switching to low-carbon materials and vehicles, and sustainable energy; and improving design and construction approaches, and road infrastructure services to support sustainable transportation. Evaluating the effectiveness of these strategies is crucial for selecting and prioritizing carbon reduction methods, ensuring cost-effectiveness, and accelerating progress toward net-zero targets. Other sectors and countries can also benefit by learning from the most effective practices, contributing to collective efforts in combating climate change.

In the highway sector, numerous efforts have been made to reduce carbon emissions, ranging from quick wins to more comprehensive long-term strategies. Quick wins, such as the adoption of energy-efficient technologies and low-emission vehicles, have shown immediate benefits as evidenced in the NH 2022-2023 annual progress report [3]. However, many initiatives focus solely on carbon mitigation without considering long-term costs, leading to sustainability challenges over time. Additionally, some promising strategies such as building more charging facilities are stalled due to budget constraints and await adequate funding to be implemented. Despite these efforts, overall progress in carbon reduction within the highway sector has been slow, and the effectiveness of these strategies remains largely unassessed. This presents a significant practice problem: without a thorough evaluation of both immediate and long-term impacts, and without proving the value-for-money, it is challenging to prioritize and implement the most effective carbon reduction measures.

Existing research has extensively explored the effectiveness of carbon reduction strategies in transportation infrastructure at various scales, comparing different design alternatives, scenarios, materials, equipment, and measures within infrastructure projects. Studies have analyzed a wide range of scenarios related to road construction and maintenance, considering factors such as pavements, materials, machinery, transport distance, energy sources, and land-use change, to identify optimal emission reduction alternatives. It has been highlighted that the most effective strategies include using low-carbon and recycled materials during the construction stage and adopting sustainable energy sources for off-road machinery during the maintenance stage [4]. Similarly, a life-cycle analysis of highway reconstruction projects studied the contribution of materials, construction equipment, resource mobilization, traffic disruption, and life-cycle maintenance to whole project carbon emissions, finding that material choice is a major factor in reducing GHG emissions, while equipment contributes minimally [5]. Another study compared the GHG emission reduction potential of ten innovative techniques in road infrastructure construction and maintenance in the Netherlands, recommending the switch to renewable energy for lighting installations, the use of low-energy asphalt, and the application of rejuvenators to achieve significant reductions [6]. However, these studies, focusing on the effectiveness of the strategies, have not provided quantifiable and comparable evaluation of the cost effectiveness, revealing a significant gap in the current literature.

This paper sets out to answer two research questions: (a) What are the latest key carbon reduction strategies in the highway sector? and (b) How efficient are these carbon reduction strategies? To address these questions, a case study database with a total of 1,046 entries from the UK NH is analyzed. Text mining techniques are used to extract cost and carbon data from the documents. Quantitative analyses were conducted where quantitative data are available to summarize the key carbon reduction strategies and the cost effectiveness of carbon reduction.

The rest of the paper is organized as follows. The Methods section provides a description of the dataset, data collection and preprocessing procedures, and the analytical methods used. The Results section reports the findings of the thematic analysis, content analysis, cost-benefit analysis. The Discussion section interprets the results, discusses the implications for policy and practice in the highway sector in the UK and beyond, and provides some limitations of the study and suggestions for future research. Finally, the Conclusions section summarizes the study and its key findings and implications for the transportation sector.

2 Methods

The UK NH operates a "Lessons learnt reporting" scheme, where its staff and supply chain can share their experiences. The "National Highways Carbon Hub" is an internal database for the sharing of lessons learnt regarding net-zero tools and resources (including case studies, webinars, and other learning materials). New case studies and resources are continually added to the database. As of the data extraction date (27 June 2024), there are 1,046 entries, with the first one added on 30 November 2017. These entries include basic information of each case, including its name, main category and subcategory, relevant Project Control Framework (PCF) Stage covered, and the date it was added. Additionally, they include the "Lessons Learned Report" as an appendix. With permission granted to access and download these documents, the researchers can extract data for analysis.

Due to the vast volume of documents, manually extracting data is impractical. Data mining techniques are applied to extract the desired information from the documents using Python. The basic process involves converting documents of different formats (e.g., .pdf, .docx, .pptx, .jpg, .xlsx, and .mp4) to machine-readable text formats, then using natural language processing techniques to identify and extract specific cost and carbon data. By automating and iterating this process for all documents, the cost and carbon data are extracted and stored in a structured format (e.g., .csv) file for further analysis. The "pytesseract" module is used to identify and extract specific cost and carbon data. Out of the 1,046 entries, 252 have cost data and 78 have carbon data, with only 46 entries containing both. A follow-up screening ensures the relevance (whether the cost data and carbon data are about the savings of carbon and the cost associated) of the extracted data, resulting in 18 entries with data regarding cost effectiveness of carbon reduction for further analysis. Figure 1 shows the process of data extraction and analysis.

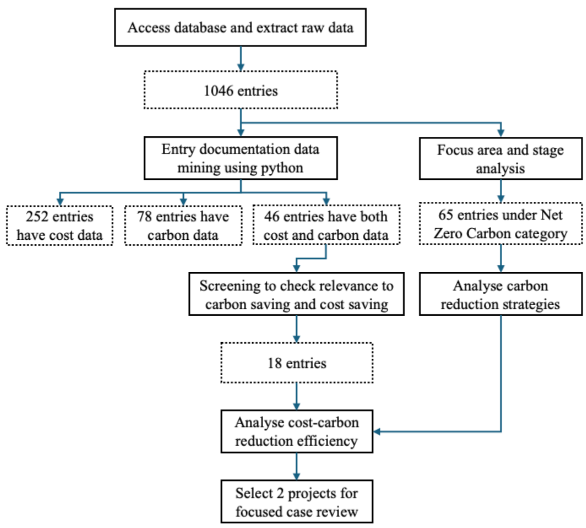

Figure 1. Data extraction and analysis process

diagram

For data analysis, the categories, subcategories, and PCF stage information are first mapped to identify the focus areas and stages of all cases in the database, as displayed in the right side of Figure 1. The strategy types are then summarized and categorized to address the first research question. Following this, the cost effectiveness of carbon reduction of the 18 cases is calculated for comparative analysis to answer the second research question. Finally, two cases are selected for a detailed investigation, examining how different strategies are employed and their respective benefits and challenges. It should be acknowledged that there is no means to assess the data trustworthiness of the data sources, therefore, the analyses are reliant on the quality of data being reported by those supplying them (i.e., NH and its contractors, suppliers). The assumption is that the database well represents the carbon management efforts in NH and its supply chain, although the extent of accuracy and comprehensiveness remains unclear to the researchers.

3 Results

3.1 Focus areas and stages

Carbon management is a very broad topic which is relevant to various project management aspects. The 1,046 entries in the "National Highways Carbon Hub" database are to share tools and resources relevant to carbon, however, some of the entries may mainly focus on other project management dimensions while carbon management was a minor focus. It is valuable to map put which areas the entries are focused while they directly or indirectly contribute to carbon management. The database classified the entries into 14 main categories including Project and programme management; Commercial and procurement; Construction; Customer and stakeholder; Carbon net zero; Consents, orders and planning; Design; Health and safety; Wellbeing and people; Environmental; Governance; Business case and funding; Specifications, standards and surveys; and Handover. Each main category contains multiple subcategories. This classification aligns with the organizational functional units and practices. Each case is classified based on the reporting unit or its closest relevance to a category (as some case may be relevant to several categories), with minor adjustments for similar terms such as merging "knowledge management admin" with "knowledge management," and "well being" with "well-being."

The Sankey diagram in Figure 2 maps out the distribution of categories and PCF stages. It shows that Project and programme management is the largest main category, with 347 entries, including major subcategories like knowledge management which include meetings, forums, workshops and competitions to share knowledge (210), innovation and continuous improvement (73). This focus reflects the critical role of strategic planning and management in achieving carbon reduction goals and underscores the importance of organizational learning and continuous improvement in carbon management. Construction cases are distributed among subcategories like road pavement (17), structures (17), earthworks (14), equipment and materials (10), road restraints (9), and traffic management (9). In the customer and stakeholder category, major subcategories include public liaison (27), roadworks customer experience (26), public consultation (15), and communication planning (14). For the commercial and procurement category, most cases fall under statutory undertakers (46), followed by social value (15 in total), contract management and supplier performance (13), and commercial assurance (11). The relatively lower number of cases in design (33 entries) indicates a potential area for improvement. Given that design and construction stages offer substantial opportunities for carbon reduction through innovative design solutions, material choices, and construction methods, it is crucial to enhance these categories during the construction and design phases for significant long-term carbon reduction benefits. Sixty-five cases fall within the Carbon net zero category, directly reporting the lessons learned about carbon management.

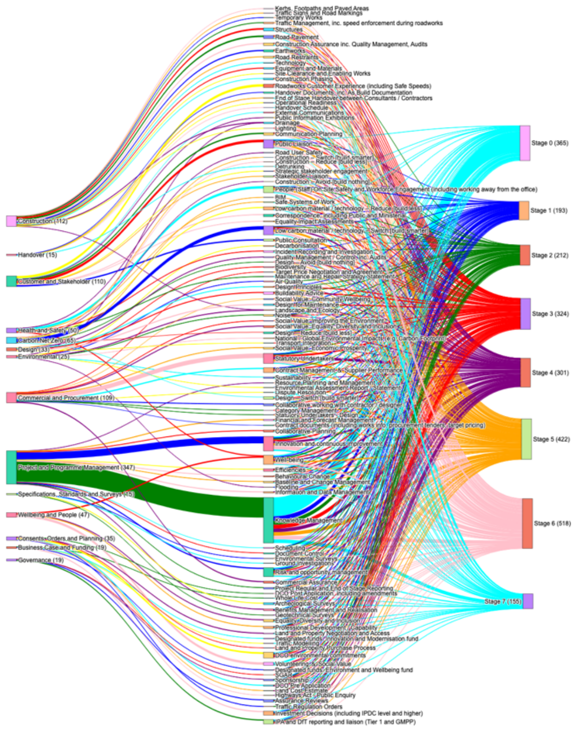

Figure 2. Category distribution of the cases

There are 8 PCF stages in total: Stage 0 to 7 from pre-project, to options, development, and construction following the project lifecycle, as shown in Figure 3. It is worth noting that with the progress of the PCF stages, the ability to reduce whole life carbon decreases as prior decisions create commitments to particular pathway [7]. Figure 3 also lists the key carbon management activities of a major project across different PCF stages. According to Figure 2, most records in the database have covered Stage 6 (construction, commissioning, and handover) with 518 entries, followed by Stage 5 (construction preparation) with 422 entries, Stage 0 (strategy, shaping, and prioritization) with 365 records, and then Stages 3 and 4, both with over 300 records. Comparatively, Stage 1 and Stage 2 for the options identification and selection, which are crucial for carbon reduction, are not very well covered in the cases.

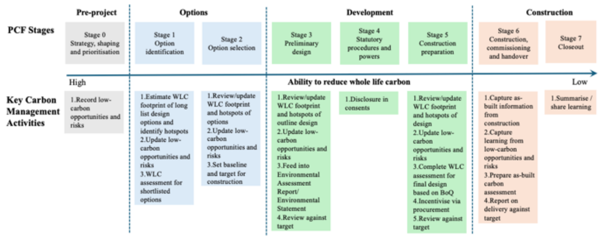

Figure 3. PCF stages and their abilities to reduce whole life carbon

The distribution of entries favors the development and construction stages, particularly Stage 6 (construction, commissioning, and handover) and Stage 5 (construction preparation). By the time projects reach these later stages, many decisions that significantly influence carbon emissions, such as material selection and design choices, have already been made. Consequently, the potential for reducing whole life carbon is considerably diminished at these stages. The underrepresentation of Stage 1 (options identification) and Stage 2 (options selection) is concerning. These early stages are critical for setting the groundwork for effective carbon reduction strategies. Decisions made during these phases have the greatest potential to influence the overall carbon footprint of a project. For instance, selecting low-carbon materials and technologies, optimizing design for sustainability, and incorporating carbon reduction goals into the project scope are best addressed early in the project lifecycle.

3.2 Carbon reduction strategies

To answer the first research question about what strategies are taken for carbon reduction, we thoroughly investigate the Carbon Net Zero entries in the "National Highways Carbon Hub" database. It is found from the reports that there are two guiding set of strategies: "Carbon Quick Wins" and carbon reduction hierarchy.

3.2.1 Carbon quick wins

To meet their Net Zero targets, NH has implemented a strategy called "Carbon Quick Wins" for major projects. This strategy is supported by a resource known as the "Low Carbon Opportunities Register", which contains a plethora of ideas to reduce carbon emissions throughout the design and construction phases. From the numerous opportunities available, the "Carbon Quick Wins" initiative advocates for the adoption of one or more innovative and mature solutions that offer additional benefits, including cost reduction or neutrality. This initiative targets projects in the design, development, and construction phases to drive carbon reduction efforts while ensuring consistency with current practices and establishing minimum expectations throughout the NH supply chain.

"Carbon Quick Wins" are required to meet five key criteria:

1. High Impact: The innovation should provide additional efficiency, health and safety, performance, and other co-benefits.
2. Cost Reduction/Cost Neutral: While there may be some initial up-front costs, the overall result should be cost-saving.
3. Carbon Reducing: The primary objective is to reduce carbon emissions.
4. No Departures from Standards: The innovation should not require additional approvals and should be supported by technical memos or pilot studies.
5. Mature Level of Innovation: The solution should have a maturity level of 4 or 5 and be applicable with little to no limitations.

Carbon quick win requirements

The "Carbon Quick Wins" strategy emphasizes both cost efficiency and carbon reduction, ensuring that initiatives provide tangible financial benefits while contributing to net-zero targets. This dual focus is crucial in gaining buy-in from stakeholders who may be hesitant to adopt new practices due to perceived costs. Ensuring that the "Carbon Quick Wins" do not require departures from existing standards is bounded by the bureaucratic hurdles and delays often associated with seeking additional approvals for new practices. This approach facilitates smoother implementation and integration of these innovations within current projects, reducing the risk of resistance from stakeholders accustomed to existing standards. Similarly, requiring a high maturity level (i.e., Innovation Capability Maturity Levels Four or Five which indicate innovation activities and resources are integrated and aligned, even synchronised [8] for the innovations ensures that the proposed solutions are well-tested and proven in real-world scenarios. By prioritizing mature innovations, NH can reduce the risk associated with implementing new technologies and increases the likelihood of successful outcomes. Overall, the "Carbon Quick Wins" strategy represents a proactive, balanced, and pragmatic approach to achieving significant carbon reductions in the short term. By leveraging high-impact, cost-effective, and mature innovations that align with existing practices, NH can drive substantial carbon reductions while maintaining operational efficiency and stakeholder engagement.

Carbon quick win examples Four "Carbon Quick Wins" strategies NH has identified include: using warm mix asphalt, eliminating equipment idling, specifying alternative mixes for ancillary concrete, sourcing renewable energy. Table 1 provides an overview of the four example strategies. They are all applicable to PCF 3, 5, 6. Two of the strategies are about low carbon materials, asphalts and concrete which are two major materials used in road construction. They produce materials with same function using alternative methods while also save costs, which makes them "quick wins" as they are effective, practical, and economically viable for large-scale infrastructure projects. Eliminating equipment idling is a straightforward yet impactful strategy with significant reduction in both carbon emissions and fuel costs, with the ability to be widely adopted with minimal investment and training. The shift to renewable energy sources is one of the most impactful strategies with the potential for up to 90% carbon reduction, highlighting its transformative impact. The cost savings, although significant in the example provided, will vary depending on the scale and duration of projects. However, the long-term benefits of reduced reliance on fossil fuels and enhanced sustainability make this strategy highly desirable.

3.2.2 Carbon reduction hierarchy

There are three types of carbon reduction decision-making strategies: Avoid (e.g., build nothing), Reduce (e.g., build less), and Switch (e.g., build smarter). Avoiding any unnecessary building has the highest ability to reduce carbon and the highest priority in decision-making, reducing the amount of work and material if building is unavoidable comes second, and switching to smarter and cleaner ways when further reduction is impossible comes last. This hierarchy is based on the whole-life carbon reduction potential of each strategy: avoid is the most effective, followed by reduce, and then switch. These strategies are applied across various aspects: low carbon material and technology, design, and construction. As shown in Figure 4, of the 48 cases focused on low carbon material and technology, 37 involve switching and 11 involve reducing. For design, six cases involve switching, six involve reducing, and one involves avoiding. There are only four cases about construction, with one on avoiding, two on reducing, and two on switching. The relatively active learning area of low carbon materials demonstrates a commitment to incorporating sustainable practices in material selection and usage. Also, a big proportion of the cases focused on switching to low carbon energy including electricity, hydrogen, and hydrotreated vegetable oil (HVO). Also, the distribution of the sixty-five cases between switch, reduce, and avoid strategies suggests a need to emphasize "Avoid" and "Reduce" strategies more, as they offer higher potential for carbon savings.

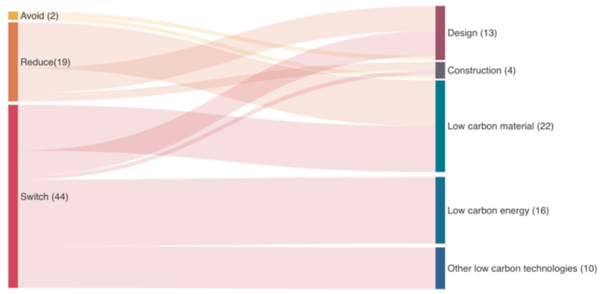

Figure 4. Carbon reduction strategies

3.3 Cost effectiveness of carbon reduction strategies

The Marginal Abatement Cost (MAC) is a key indicator for measuring the cost of carbon reduction [9]. It represents the marginal cost per tonne CO_2e abatement [10]. To assess carbon reduction cost effectiveness, the MAC is calculated by dividing the extra cost/benefit by the total carbon reduction. To answer the second research question, the authors extracted the data from the 18 database entries with both cost change data and carbon reduction data available and valid (which means the scope of cost change data and carbon reduction data aligns, as there are cost saving of the whole project while carbon reduction of a single initiative) and calculated the MACs, which are shown in the last column of Table 2, with the unit £/tCO_2e. Negative MACs indicate cost saving while reducing carbon, whereas positive numbers imply extra costs. Seventeen of the 18 cases have negative MACs ranging from -60£/tCO_2e to -11,111£/tCO_2e, indicating that in these cases, with one tonne of CO_2e reduced, £60 to £11,111 are saved. Only one project required extra investment, with a marginal cost of about £5 per tonne of CO_2e.

The data reveals that significant cost savings can be achieved alongside carbon reduction, as evidenced by the predominantly negative MAC values. However, the significant variance in MAC values among projects indicates that the cost-effectiveness of carbon reduction strategies can differ widely based on project specifics and

Table 1. Summary of Carbon Quick Wins strategy examples

Strategy	Explanation	Carbon reduction potential	Cost saving
Warm mix asphalts (WMAs)	Asphalt mixtures made at lower temperatures—up to 40°C cooler than regular Hot Mix Asphalts (HMAs).	5-10% in production compared to HMAs	Circa 20% shift output increase, saving around £70 million/year across NH
Eliminating equipment idling	Eliminating the operation of equipment, machinery, or vehicles while they are not actively engaged in productive work.	15-18.6% according to cases	£10,000 on fuel savings across 16 machines in one case
Specifying alternative mixes for ancillary concrete	Designated GEN (general) /RC (reinforced) /FND (foundation) concrete mixes are an alternative to Standardized prescribed (ST) concretes, with a more refined mix design compared and require less cement in the mixture to attain equivalent strength levels.	25-50%	Saving £9/m3 for non-structural concrete used
Sourcing renewable energy	Power sourced from naturally replenished resources such as sunlight, wind, water, geothermal heat, and biomass.	up to 90%	Save £3,700 over ten weeks using hydrogen power generation and photovoltaic panels compared to conventional diesel generators

Table 2. Marginal Abatement Cost of 18 cases

Case	Strategy	Category	PCF Stage(s)	Carbon Saving (tCO2e)	MAC (£/tCO2e)
C1	Avoid	Low carbon material	3,4,5,6	2,221.6	-3,632
C2	Switch	Design	3,5,6	5,721	-422
C3	Switch	Low carbon material	3,4,5,6	2,727	-2,180
C4	Switch	Low carbon energy	5,6	0.341	-352
C5	Switch	Low carbon energy	3	99,937	5
C6	Switch	Low carbon energy	4,5,6	164	-504
C7	Switch	Construction	5,6	498.56	-468
C8	Switch	Low carbon material	3, 5,6	8,100	-1,926
C9	Switch	Design	5,6	149.08	-60
C10	Switch	Low carbon energy	3	140	-250
C11	Switch	Low carbon energy	5,6	21.1	-175
C12	Switch	Low carbon material	6	70	-214
C13	Reduce	Low carbon material	3,4,5,6	115.4	-303
C14	Reduce	Design	3,4,5,6	408	-2,941
C15	Reduce	Design	6	130.5	-530
C16	Reduce	Low carbon material	3,4,5,6	339.7	-2,208
C17	Reduce	Construction	6	174	-3,448
C18	Reduce	Low carbon material	5,6	90	-11,111

implementation practices. Eleven of the eighteen cases adopted "Switch" strategy and only one reported "Avoid" as a guiding strategy. The "Avoid" strategy shows more significant cost saving than the average of "Switch" strategy which generally demonstrate cost savings, though with varying extents. Even the "Reduce" strategy (average MAC is -3,423.5 £/tCO_2e) seems more effective than the "Switch" strategy (average MAC is -595.09£/tCO_2e).

Twelve of the projects approached low carbon material, energy, and technology, with seven emphasizing materials, four using better design, and only two adopting better construction methods. The average MAC of low carbon material is -3,096.29 £/tCO_2e, it is -283.67 £/tCO_2e for low carbon energy, -212.5 £/tCO_2e for other low carbon technologies, -988.25 £/tCO_2e for design approaches, and -1,958 £/tCO_2e for construction approaches. While there is not a large dataset and there is a lot of variation in MACs, the adoption of low carbon materials is an area where lessons learnt reporting is indicating particularly cost effective, especially for the C18 case. The two construction cases, particularly C17, also achieved substantial cost-effectiveness, followed by design approaches. In contrast, low carbon energy and other technologies seemed less cost-effective.

The PCF Stages of implementation range from 3 to 6. Most cases introduced carbon reduction measures at Stages 5 and 6, which are relatively late in project life-cycle. Interestingly, the average MAC decreases from Stage 3 (-1,550.17 £/tCO_2e) to Stage 6 (-2,098.40 £/tCO_2e). The absence of early-stage interventions (especially Stages 0, 1 and 2) within the documented cases does not necessarily mean that the early stages were neglected in practice, it only links to the fact that the late stage case studies were reported in the Carbon Hub dataset more than the earlier stages.

The C18 case, with the lowest MAC, indicates the best cost efficiency in carbon reduction. This £120 million highway construction project reduced emissions by collaborating with another nearby project (less than 6 miles away) for earthworks, reusing 73,350m^3 of spoil. This reduced the use of primary natural resources and material haulage distance by around 50,000 lorry miles, resulting in an estimated net cost saving of about £1 million. The carbon reduction of 90 tonnes CO_2e was primarily due to reduced lorry miles. In summary, this is a special case where the economic benefit is significant while the carbon reduction of 90 tonnes CO_2e may not seem as impactful.

The C5 case required extra investment. It assessed the Renewable Energy Guarantees of Origin (REGO) Certified Electricity at PCF Stage 3. This scheme involves using a tunnel boring machine to drill a tunnel at least two miles long. The machine is very energy-intensive, predicted to consume 197,407,795 kWh of electricity, with the total estimated electricity usage of the project being 202,194.47 MWh, which equated to 99,937 tCO_2e in 2018 coefficients. By using REGO Certified Electricity, grid emissions can be reduced to virtually zero. It was estimated to require £537,837.29 in additional costs in 2018 to buy REGO Certified Electricity, resulting in a MAC of £5.38/tCO_2e. While this is a positive number, it is relatively low, suggesting that the investment in REGOs is a cost-effective way to achieve significant carbon reductions.

Putting the MACs in the wider context, we can evaluate the cost effectiveness of the carbon reduction efforts in UK highway sector. The UK government assumed a traded carbon price of £70/tCO_2e at 2030 [11]. As estimated by Yue et al. [12], the transport sector can achieve full decarbonization in 2050 with MAC at €518/tCO_2e. Comparing to these benchmark numbers, the UK highway sector's carbon reduction strategies are very cost effective.

4 Discussion

The analysis highlights several critical issues that impede the effective evaluation and implementation of the cost effectiveness of carbon reduction strategies in the UK highway sector. Notably, the lack of comprehensive cost and carbon data significantly limits the ability to assess the cost-effectiveness of various measures. Out of 1,046 entries, only 46 contain both cost data and carbon data, and just 18 entries were suitable for comparative analysis after screening. Moreover, the current dataset's inconsistency and rough granularity further complicate the assessment process. The scarcity of detailed, granular data hampers robust evaluation and informed decision-making, underscoring the need for more thorough data collection and reporting to include detailed cost and carbon data for all projects.

The comparative analysis of 18 cases reveals significant variability in the MAC across different initiatives. This variability indicates that the same strategy may have different cost-effectiveness in different cases, depending on the specific context and implementation. The findings suggest that a standardized method for measuring the cost and impact of carbon reduction is necessary for future research.

"Carbon Quick Wins" offer practical, cost-effective measures with significant carbon reduction potential. Adoption and scaling of these low-carbon opportunities across NH projects can maximize their impact, with cost savings reinvested into further initiatives. Building on them, a balanced application of the "Avoid", "Reduce", and "Switch" strategies should be encouraged. Enhancing "Avoid" and "Reduce", integrating various carbon reduction strategies during the option and design phases can maximize carbon savings.

The study's limitations include the lack of comprehensive data of all the carbon management practices apart from the lessons learned and the lack of sources to validate the data trustworthiness [13, 14]. Future research should focus on developing standardized methods for measuring cost and carbon impact and collecting more detailed data [15, 16]. It is also recommended that government should drive the change to require organizations to report betterer quality cost and carbon reduction data with higher granularity. In the meantime, GHG and Environmental, Social, and Governance (ESG) reporting standards should provide clear guidance on how to report the cost and carbon data simultaneously. The technology sector is also encouraged to develop tools to capture carbon reduction and cost information together. Additionally, government policy should explore the long-term impacts and costs of carbon reduction initiatives to provide a more holistic view of their effectiveness and make the most cost-effective carbon reduction policies.

5 Conclusions

The analysis of the 1,046 "Lesson Learned Reports" on carbon management in the UK "National Highways Carbon Hub" found that the primary focus area is "Project and programme management", with a significant emphasis on the construction stage, which occurs late in the lifecycle and has limited impact on whole life carbon reduction. The study highlights the adoption of four "Carbon Quick Wins" approaches and the carbon reduction hierarchy (Avoid-Reduce-Switch), noting that "Avoid" strategies, although most impactful, are less frequently adopted compared to "Reduce" and

"Switch" strategies, as suggested by the number of lessons learnt reports. Filling the gap of cost effectiveness of carbon reduction methods, the analysis of 18 cases using marginal abatement cost (MAC) calculations revealed considerable variability. The results suggest that the cost-effectiveness of carbon reduction strategies can vary significantly depending on the natural of the initiatives and the context they were adopted.

Another key implication from case studies is the significant lack of comprehensive cost and carbon data, with only 46 entries containing both data types and a mere 18 cases suitable for comparative analysis. Even for these limited available data, it is difficult to ensure the data trustworthiness. This scarcity of detailed data impedes the robust evaluation of the cost-effectiveness of various measures, emphasizing the need for standardized and granular data collection methods.

Policy implications for the transportation infrastructure sector include enhancing the focus more on option and design phases, adopting a balanced strategy application. Developing standardized methods for measuring cost and carbon impact, collecting more detailed data, and exploring long-term impacts and costs will provide a more comprehensive understanding of the effectiveness of carbon reduction initiatives. By addressing these areas, the transportation sector can make substantial progress towards net-zero targets and contribute to broader climate change mitigation efforts.

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