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Understanding the contribution of tunnels to the overall energy consumption of and carbon emissions from a railway

James A. Pritchard, John Preston

Transportation Research Group, University of Southampton, Building 176, Boldrewood Campus, Southampton SO16 7QF, United Kingdom

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ABSTRACT

Tunnels can contribute significantly to the overall energy consumption and carbon emissions of a railway, both in terms of embodied energy and emissions (those associated with the materials and the construction process) and in terms of operational energy and emissions (due to the increased air resistance experienced by a train inside a tunnel). Although tunnels may be a necessary component of railway infrastructure, it is important that their impact on carbon emissions is fully understood, especially when comparing the railway with other modes. This paper reviews existing literature and uses a case study to develop understanding. Trade-offs between embodied and operational energy and emissions are explored.

1. Introduction

Tunnels are an important component of railway infrastructure. In Europe, about 10% of conventional and high-speed railway lines are in tunnels (Network Rail, 2009, Table 3.3), whilst the figure for some suburban networks is much higher. For example, 45% of the London Underground network is in tunnels (Transport for London, 2015).

The requirements of the vertical alignment of railway lines in undulating ground often mean that tunnels are necessary (HS2 Ltd, 2013), whilst they may also be desirable for other reasons, such as the avoidance of surface-level disruption in an urban area. In terms of sustainability, tunnels could help avoid social and economic concerns arising from the bisection of urban communities or rural farmland, and environmental concerns surrounding noise and visual intrusion. However, tunnels also raise potential sustainability concerns of their own, especially regarding energy consumption and carbon dioxide (CO_2) emissions.

The energy consumption and embodied CO_2 emissions associated with tunnel construction appear to be disproportionately high; Network Rail (2009, Table 2.10) suggest that the greenhouse gas (GHG) emissions (in terms of carbon dioxide equivalent (CO_2e)) from sections in tunnels are between four and five times higher per route-km than the open sections. Workman and Soga (2004) estimated that the embodied emissions associated with the construction of just 7.5 km of twin-bore tunnels for the Channel Tunnel Rail Link (CTRL) in the UK accounted for 2.1% of all emissions associated with the UK construction industry in 1999. A key reason for this is that tunnel construction utilises equipment which consumes a lot of energy (Ahn et al., 2010). Operationally, the air resistance experienced by a train running through a tunnel is higher than that experienced by a train on open track, and the resulting increase in energy consumption can be assumed to lead to a similar increase in CO_2 emissions, depending on how the train is powered and how clean the electricity grid is assumed to be.

Developing a proper understanding of the energy consumption and CO_2 emissions associated with the construction and operation of railway tunnels is important, for a number of reasons. Firstly, although energy efficiency may be seen as a relative strength of rail compared with other modes (Armstrong and Preston, 2010), it is clear that tunnels can have a potentially significant impact. Modal comparisons used to inform future transport policies must adequately take tunnels into account if reducing energy consumption and CO_2 emissions are important goals. Secondly, not all rail tunnels are necessary, and it is important that designers of railway infrastructure are properly informed when weighing up the merits (sustainability-related and otherwise) of including a tunnel. Finally, it is

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thought that the design of a tunnel can affect the relative sizes of the embodied and operational energy consumption and CO_2 emissions, and that there may therefore be an optimum design for minimising overall energy consumption and emissions.

Building on previous work (Pritchard, 2015), this paper begins by exploring the embodied energy and CO_2 emissions associated with railway tunnels, before going on to consider operational energy consumption and emissions; in both cases, relevant literature is reviewed where appropriate, and data from part of the new "Crossrail" underground railway in London are considered. Whereas existing studies found in the literature tend to focus solely on either the embodied or the operational emissions, these data for Crossrail are valuable because they cover the embodied emissions and operational emissions of the same system, allowing the overall impact to be considered. Finally, some general calculations are undertaken to demonstrate the way in which the size of the tunnel diameter may change the overall energy consumption and emissions.

2. Embodied energy and emissions

Workman and Soga (2004) define the embodied energy of an item in simple terms as "the total energy that can be attributed to bringing that item to its existing state." A parallel definition could be used for embodied CO_2 emissions, noting that there is typically a direct link between energy consumed and CO_2 emissions (such emissions may occur directly on site or indirectly as a result of electricity generation). Embodied energy and emissions in infrastructure should take into account both the materials used and the processes involved in construction. The embodied energy and emissions of the materials should include raw material extraction, refining, processing and manufacturing processes, and the transportation of the materials, both between processes and to the construction site. Quantifying these things is not straightforward, and the data are subject to uncertainty and variation. A key reason for this is that the boundaries are often blurred — for example, when considering the transportation of materials, it could be argued that a suitable proportion of the overheads of the transportation company used should also be included in the calculations, in addition to the direct energy and emissions arising from moving goods between two points. The problem with such diligence is that obtaining detailed data can be hard, and the calculations can be dependent on individual interpretation. There does not appear to be a consistent standard for determining boundaries, and different data sources may be based on different assumptions. Allwood et al. (2012, p.20) note that "the materials producing industries are highly sensitive to the presentation of energy and emissions data and … only report the most positive story.".

Materials aside, the embodied energy and emissions of the construction processes are mainly attributable to the vehicles and machinery used, but may also include other factors, such as the transport of personnel to and from the construction site. Workman and Soga (2004) additionally suggest that embodied energy and emissions should also include appropriate proportions of the energy and emissions associated with the vehicles and machinery used, and should take into account the construction and maintenance of associated buildings and roads.

After introducing embodied energy and emissions in a little more detail, this section includes discussions on choosing an appropriate metric for presenting the data, and on accounting for the life span of infrastructure. A single figure for each of the embodied energy and emissions can be calculated, representing the total energy expended by and CO_2 emissions from the infrastructure construction. Although this can be valuable, disadvantages of presenting the data in this format include the fact that it may not be easy to make meaningful comparisons with other infrastructure projects or with other aspects of the railway. This is because total figures do not take into account the lifespan of the infrastructure or the usage of the system. For the same reason, it can also be difficult to include the embodied energy and emissions of maintenance activities.

Data from existing studies are then presented, beginning with some work on new high-speed railway lines, illustrating the significance of railway tunnels compared with the rest of the infrastructure.

2.1. Embodied energy and emissions in the materials themselves

Data are available for the embodied carbon and energy in construction materials, for example in a database compiled at the University of Bath (Hammond and Jones, 2011). This means that it is theoretically possible to estimate the embodied carbon and energy in the materials of a particular infrastructure project, although detailed knowledge of the quantities and of the types of material is required. In the case of concrete, for example, the embodied energy and carbon can vary significantly, and Hammond and Jones strongly advise against simply using the "general" value they provide. Stimpson (2011) cites a recent project which concludes that the University of Bath data for embodied carbon in concrete is inaccurate. Whereas the University of Bath based its values for some materials on generic secondary data, the Concrete Pipeline Systems Association (CPSA) collected primary data from its member organisations. In this case, the findings suggest that University of Bath figure was likely to be overstating reality, which is arguably better than underestimating embodied carbon but is still not ideal.

Some aspects of railway infrastructure, such as the track itself, are already well documented; for example, details of the most popular track designs are given by Kiani et al. (2008) and can — for example, in the case of the Rheda 2000 Slab Track System — be supplemented by details from the manufacturer themselves (Rail.One GmbH, 2011). Other aspects of the infrastructure are currently more difficult to quantify — for example, tunnels and bridges tend to be more bespoke — although estimations are available in current literature (for example, Baron et al. (2011)). It is also worth noting that much of the available data for materials are subject to various assumptions.