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RESEARCH PAPER

Materiality and sustainability transitions: integrating climate change in transport infrastructure in Ontario, Canada

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ABSTRACT
Infrastructure threatens to lock-in societies to fossil fuels unless something is done now. This is because infrastructure lasts for such a long time, meaning that any infrastructure built or rebuilt now will last well into the twenty-first century – until the end of the century, in some cases. Consequently, there is a need to integrate climate change into infrastructure now or societies will be left with infrastructure designed around unsustainable socio-technical systems (such as combustion engines, roads, and suburbanization). Such change is conceptualized in the literature as a sustainability transition. However, any attempts at such transitions have to address the 'materialities' of infrastructure systems (physical form, environmental context, and so on). In this paper, I develop the concept of 'socio-material systems' and apply it to transport infrastructure in Ontario, Canada.

Introduction

Extreme weather events have brought considerable attention to bear on the potential and actual impacts of climate change on municipalities and communities. These range from the destruction caused to the eastern seaboard of the United States by Hurricane Sandy in 2012, through to the devastating floods in Calgary, Canada in 2013, to the snowstorms in eastern Canada and the US in early 2015. Whether these are the result of climate change is beside the point; what they illustrate are the significant effects that extreme weather events can have. Such weather events have been increasing in frequency and intensity over the last few years, suggesting that worse is yet to come. While the human cost of these events is obviously appalling, the socio-economic costs have also started to attract the attention of the public, politicians, policy-makers, the insurance industry, and professional groups (Sturm and Oh, 2010).

Extreme weather events and their consequences provide an important illustration of the drive behind the search for 'sustainability transitions' to a low-carbon society – an area of increasing academic interest in the last decade or so (Geels, 2002, 2004; Geels and Schot, 2007; Shove and Walker, 2007; Frantzeskaki and Loorbach, 2012; Lawhon and Murphy, 2012; McCormick *et al.*, 2013; Tyfield, 2014). How these sustainability transitions are meant

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to happen is still contested, but one area where there is a definite and urgent need for debate – and, even more urgent, for action – is the adaptation of core infrastructure (e.g. roads, transit, energy, water) to changing weather and climate patterns (Monstadt, 2009; Frantzeskaki and Loorbach, 2010; Markard, 2010; Bulkeley *et al.*, 2013). As noted in a recent OECD (Organization for Economic Co-operation and Development) report, countries like Canada (as well as many others) face a growing infrastructure crisis as the need for both new infrastructure and the replacement of old infrastructure rises (Corfee-Morlot *et al.*, 2012). Consequently, there is now a major opportunity to integrate climate change into the planning, design, construction, and maintenance of new and old infrastructure.

The key problem facing many countries, however, is that infrastructure has a long lifespan, which means any changes made now are likely to last for several decades. Moreover, it is not clear whether or how climate change is being integrated into new or rebuilt infrastructure. Critically, such infrastructure has to be thought of as a 'socio-material system' in which physical components are bound up with socio-technical components. This means that any transition is complicated by interacting socio-technical and material opportunities and limitations. Without action now, for example, infrastructure planning, design, and development could reinforce 'carbon lock-in' (Unruh, 2000), especially through failure to integrate climate change mitigation and adaptation strategies in the physical manifestation of infrastructure systems (e.g. building roads rather than public transport). The threat of infrastructure lock-in could be profound in that it could create physical limits that inhibit societal capacities to develop or choose particular sustainability transition pathways.

In the light of these concerns, it is necessary to understand whether and how climate change is being integrated into infrastructure development. My aim in this paper is to ask three related questions: (1) How should we conceptualize the materiality of infrastructure? (2) What are the examples and implications of materiality to infrastructure innovation? and (3) What are the barriers to such innovation? In order to answer these questions, I first develop the analytical concepts of socio-material systems by drawing on the existing literature on sustainability transitions, infrastructure, and socio-technical systems. I then use these concepts to analyze empirical material from a research project carried out in Ontario, Canada in 2012 and 2013 by looking at the integration of climate change in three transport infrastructure projects at different stages of their life cycles.

Sustainability transitions and socio-material systems

As Shove and Walker (2007) note, recent sustainability transitions literature owes a clear debt to earlier work on large-scale, technical systems pioneered by Hughes (1983, 1987). More recent literature puts greater emphasis on social aspects of these systems. For example, Frank Geels (2002, 2004) and Geels and Schot (2007) argue that socio-technical systems, innovation governance, and sustainability transition are constituted by social and technical components changing in relation to each other, often in complex and uncertain ways.

Geels (2002) develops an approach he calls the 'multi-level perspective' (MLP) in which he conceptualizes sustainability transitions as multi-scalar, involving socio-technical change by social actors (e.g. science, technology, users, government) at the landscape, regime, and niche scales. On the one hand, existing and stable socio-technical regimes (e.g. petroleum-powered automobiles) are dynamic in that emerging niche innovations (e.g. electric cars) can enter, align with, and then change existing regimes (endogenous pressures). On the other hand, the broader landscape (exogenous pressures) can put pressure on regimes to change (e.g. climate change policy) (Geels, 2002; see also, Geels and Schot, 2007). According to Tyfield (2014, p.586), the strength of this MLP framework is that it avoids the tendency, especially in policy circles, to 'focus on new technologies to the exclusion of both the irreducible social factors and the systemic nature of stabilised socio-technical settlements and their transition'. Thus, one of the key intellectual insights provided by the sustainability transitions literature is that climate change, and other environmental issues, cannot be resolved by technological innovation alone; societal innovation is also necessary.

This raises a series of issues of how to promote sustainability transitions in core infrastructure developments (e.g. roads, transit, utilities). As Monstadt (2009, p.1926) argues, 'Key socioecological problems like climate change, air and water pollution, resource shortages, etc. can thus only be tackled through the transition of existing infrastructure'. Within the sustainability transitions literature, infrastructure is an increasingly important topic for a number of reasons. While the work of Geels (2002) and others on the MLP has proved fruitful in some areas, it can be pushed further in other areas. First, Shove and Walker (2007) highlight how notions of sustainability transition – themselves contested and contestable – are frequently aligned with resource and energy efficiencies in infrastructure development, rather than the wholesale transformations of infrastructure and its social purpose. Second, Tyfield (2014, p.594) notes the clear power dimensions to any transition, emphasizing that infrastructure is but one part of the 'knowledge-power technologies that specifically enable or constrain' social action. Finally, Truffer and Coenen (2012) argue that some transitions involve long-term shifts and policy changes – an obvious case being infrastructure development – necessitating a different, more reflexive approach to transition. While the literature on transition management (e.g. Kemp and Rotmans, 2009) might represent one way to deal with such longevity issues, transition management has 'been accused of adopting an overly linear and mechanistic view on the politics of transformation, power and discourse' (Truffer and Coenen, 2012, p.6). In contrast, there is need for a careful conceptualization of infrastructure in order to take its material particularities (e.g. its relatively stable physical longevity) into account.

Infrastructure can be thought of in a dual sense (see Geels 2002, 2004). The sustainability transitions literature conceptualizes socio-technical systems as a diverse array of elements 'including technology, regulations, user practices and markets, cultural meanings, infrastructure, maintenance networks and supply networks' (Geels cited in Lawhon and Murphy, 2012, p.357). Of these, infrastructure stands out as the one element with particular material characteristics (Monstadt, 2009). Infrastructure is defined as only one element in a socio-technical regime, but it can also be thought of as part of the (physical) landscape in which regimes operate, evolve, and change. Infrastructure is, then, both part of a socio-technical regime *and* a constitutive part of that regime's environmental context (i.e. landscape). However, as Furlong (2010, p.465) notes, current debates about socio-technical systems rarely discuss this latter aspect, what she calls the 'production of space and nature', and what others see as infrastructure's role as the 'central interface between nature and society' (Monstadt, 2009, p.1935).

So, while Geels (2002) positions infrastructure inside the socio-technical regime, it is critical – analytically speaking – to examine the materialities of this infrastructure; that is, its constitutive role as part of the landscape or environment. This paper follows Mitchell (2011) and others (e.g. Graham and Marvin, 2001; Monstadt, 2009; Markard, 2010; Birch and Calvert, 2015) in conceptualizing materiality as both shaping and being shaped by socio-technical relations. Drawing on ideas in science and technology studies (STS), Mitchell (2011) argues that physical materialities are necessarily political in that they generate and limit certain political possibilities – for instance, coal promoted the expansion of labour movements in nineteenth-century Britain, while oil stymied the development of labour movements in the twentieth-century Middle East. Whereas Mitchell is concerned with the political materialities of fossil energy, his arguments are applicable in other cases. For instance, Birch and Calvert (2015) argue that bioenergy has particular political materialities resulting from the biophysical characteristics of biomass, including its immobility, low energy density, and transboundary nature. For example, to be viable, biomass needs to be harvested in distributed locations and then shipped to a central processing site for densification before being shipped again for use in advanced biofuel refineries. It would be convenient to think of these materialities as deterministic and path-dependent, but this would ignore the ways in which materialities and socio-technical relations are co-constructed. This comes across in the work of Graham and Marvin (2001, p.215), who argue that although networked infrastructure systems represent physical legacies which shape and configure urban spaces and networks, they are also increasingly unbundled and splintered by specific social actors (e.g. planners) applying specific knowledge (e.g. cost-benefit analysis) and practices (e.g. public-private financing) (see Birch and Siemiatycki, 2016). Thus, it is important to combine the political *and* material in the analysis of infrastructure.

The intention in this paper is to analyze these political materialities in relation to infrastructure. However, it is important to acknowledge that different infrastructures have different materialities. This paper focuses on transport infrastructure, which entails three key considerations from a sustainability transitions perspective. First, transport infrastructure's physical lifespan means that it changes at a very different pace from other parts of the socio-technical regime (see Geels, 2002); roads and routes last several decades, if not whole centuries. Second, it is difficult to analyze current and future sustainability transitions in transport infrastructure because much of the existing analyses focus on long-term, historical change. Consequently, it is important to adopt units of analysis that enable an examination of current and ongoing issues and transitions (e.g. low-carbon innovation in response to climate change). Third, infrastructure has a materiality to it that differs from the other regime elements highlighted by Geels (2002). In STS, for example, such scholars as Star (1999) stress the embeddedness, scope, and invisibility of infrastructure generally speaking. More specifically, transport infrastructure is often treated as the environmental context (or landscape) in and through which social actors operate. Conceptualizing the materiality of transport infrastructure requires the analytical foregrounding of the physical characteristics of the infrastructure.

Consequently, it makes sense to theorize transport (and other) infrastructure as socio-material systems rather than socio-technical ones (Birch, 2013). That is, infrastructure can be conceived of as a social, technical, *and* material system in which the physical shape and form of infrastructure plays an important configuring role in socio-technical relations (and is configured in turn by these socio-technical relations). From this perspective, the analytical contribution of this paper is to identify and understand the socio-material innovation potential and limits of transport infrastructure as they relate to sustainability transitions. Relevant limits include the bio-physical (e.g. size, weight); the environmental (e.g. precipitation, flooding); and limits related to lifespan (e.g. adaptability, resilience, redundancy) and life cycle (e.g. decay, renewal, maintenance).

Research design and methods

This paper draws on empirical findings from a research project which was carried out in 2012 and 2013 and looked at three transport infrastructure projects in Ontario, Canada. The project was specifically concerned with identifying whether and how climate change was integrated in the planning, design, construction, and renewal of transport infrastructure in Ontario. It was also concerned with the implications of these issues for the engineering profession (see Birch and Wudrich, 2013, 2015). This latter aim arose because the Ontario Centre for Engineering and Public Policy (OCEPP) – the now-defunct policy wing of Professional Engineers Ontario (PEO) – was a research partner in the project.

Methodologically, the unit of analysis for the research was the engineering profession associated with transport infrastructure, chosen for three reasons. First, the broader project was concerned with the implications of integrating climate change into infrastructure development for the engineering profession. Second, the conceptual framing of infrastructure innovation as a socio-material process meant that the research was interested in more than just the technical or physical artefact (e.g. road, bridge, railway). Rather, it was important to identify the knowledge, practices, discourses, and actors that inform its development. Third, infrastructure has a life cycle (e.g. planning, construction, use, renewal) that necessitates taking a multi-project approach in order to understand the varied ways that climate change is integrated at different stages in the life cycle (e.g. in planning, in design, in construction, in use) rather than looking at infrastructure historically, when climate change might have been a lesser concern. Therefore, three transport infrastructure projects were chosen at different points in the infrastructure life cycle: planning and design; construction; and renewal/repair. This enabled analysis of how engineers are integrating climate change at different points in the infrastructure life cycle. Transport infrastructure was selected because it is implicated in both climate change mitigation (e.g. emissions reductions) and adaptation (e.g. flood risks). The type of transport infrastructure represented by the three projects has not been specified in order to ensure the anonymity of the informants.

The research involved a two-stage methodology. First, using secondary policy literature, the main policy strategies and activities of the municipal, provincial, and federal governments in Ontario and Canada were mapped. Second, using in-depth and semi-structured interviews with key informants, it was possible to identify how climate change was being integrated in infrastructure projects and the barriers to low-carbon innovation. A total of 30 people were interviewed, mostly engineers involved in the three projects, but also ancillary professionals (e.g. architects) and policy-makers (e.g. city officials, standards developers). Informants included people involved in the planning, design, or construction of the projects, and included public and private sectors actors. Ethical clearance was received from the author's university and the interviews were analyzed using the qualitative software program NVivo.

It is important to note some of the limitations of this research design and approach. First, since the focus is on the engineering profession, analysis is necessarily limited to engineers as a social actor, although they are a crucial actor in these debates. Cost necessarily limited the ability to extend the fieldwork to other social actors. Second, and in follow-up, the focus on the engineering profession meant that analysis of infrastructure as a socio-material system requires further research to examine other social, political, and economic actors implicated in infrastructure development (e.g. government and business). Finally, it is important to note that the physical and social constituent elements that make up core infrastructure are quite varied, meaning that the discussion here is specific to transport infrastructure. Nevertheless, the analysis still has wider analytical relevance for other infrastructure (e.g. energy utilities and buildings). Generally, then, it is important to remember that the analysis here reflects the specific focus on the engineering profession and transport infrastructure. However, this does not mean that the analysis is not an important contribution to debates about innovation in infrastructure developments.

Sustainability transitions in transport infrastructure: the case of Ontario, Canada

This empirical section provides some background to the discussion with an outline of climate change policy in Canada and Ontario. It also demonstrates the usefulness of the concept of socio-material systems to the analysis of infrastructure. It then analyses the integration of climate change in transport infrastructure from this perspective in order to think through different forms of infrastructure innovation. The section concludes by analyzing the barriers to infrastructure innovation.

Background: climate change policy in Canada and Ontario

Neither Canada nor Ontario is a leader in climate change policy, whether through mitigation or adaptation policy (Mees and Driessen, 2011). Nevertheless, federal and provincial governments are interested in climate change policy. The evolution of policy reveals some of the distinct cleavages in Canada's political structure. Because the focus is on the integration of climate change in transport infrastructure, a range of relevant policy strategies (e.g. in standards and regulations) in Ontario and Canada from the mid-2000s is identified. The term 'policy' is used in a broad sense to mean an array of social actors who influence policy-making (e.g. business, trade associations, NGOs, professional associations, community groups). Policy extends beyond government and state.

Policy strategies focusing on climate change and infrastructure are relatively new to Canada. Two early examples at the federal level are Infrastructure Canada's 2006 literature review, *Adapting Infrastructure to Climate Change in Canada's Cities and Communities*, and Natural Resources Canada's 2007 report, *From Impacts to Adaptation: Canada in a Changing Climate* (Infrastructure Canada, 2006; NRC, 2007). Both policy strategies emphasize the need for the federal government to integrate climate change into infrastructure planning and decision-making. Other national-scale but non- or quasi-governmental organizations have produced similar policy strategies. For example, Engineers Canada produced a report in 2008 called *Adapting to Climate Change*; the now-defunct National Roundtable on the Environment and Economy (NRTEE) produced a report in 2009 called *True North: Adapting Infrastructure to Climate Change in Northern Canada* (NRTEE, 2009); and the Federation of Canadian Municipalities (FCM) produced reports in 2011 and 2012 called *Building Canada's Green Economy* and *The Road to Jobs and Growth* (FCM, 2011, 2012). These non- or quasi-governmental organizations produced policy strategies because of the political position of the Conservative federal government of the time (2006–2015). This Conservative government took a strong anti-climate change policy stance (Winfield, 2012), leaving other policy-makers to champion specific strategies.

The federal political situation – which has since changed – resulted in a rescaling of climate change policy downwards, evident in Ontario. The provincial government developed a series of climate change strategies and policies in the same period. Examples include the establishment of an expert panel on climate change adaptation in 2007, which produced a report in 2009 called *Adapting to Climate Change in Ontario*; the creation of a climate change action plan in 2011; and a more recent climate change consultation (MOECC, 2015). Similar initiatives have been taken at the municipal level as well, with Toronto a key Canadian example. Toronto produced a Climate Change, Clean Air and Sustainable Energy Action Plan in 2007 and a Climate Change Adaptation Strategy in 2008 (MacLeod, 2011).

What is evident from these activities is that as the federal government retreated from climate change policy-making, provincial and municipal governments stepped in to develop their own strategies. Examples here include the 2010 introduction by Toronto of the Toronto green standard, which is a list of development performance measures to promote sustainability; Ontario's 2011 capital infrastructure plan that incorporates climate change into infrastructure development and asset management; and Ontario's 2014 provincial policy statement setting out the requirement to consider the implications of changing climates (Birch and Wudrich, 2015).

Infrastructure as socio-material system

Those interviewed saw infrastructure as more than a large, technical system (Hughes, 1983, 1987). Engineers, for example, undertook development activities (e.g. planning, design, construction) from the perspective that infrastructure is both a social *and* a material phenomenon. They saw transport infrastructure as a socio-material system in which socio-technical relations and physical materialities co-constitute one another. This perspective is evident in a range of concerns, from operational efficiencies and inter-dependencies (on the socio-technical side) to passive design and smart systems (on the material side).

A number of informants highlighted the importance of the operational costs and efficiencies inherent in infrastructure use, especially in relation to buildings (e.g. subway stations). The representative of a building materials trade association claimed that:

> The cost of operating a building over the life of the structure uses so much more energy than the energy that we'd use to construct it, it dwarfs it ten to one.

The informant highlights the importance of considering the inter-dependencies of the various social, technical, and physical components in infrastructure systems (e.g. Frantzeskaki and Loorbach, 2010). The same informant commented:

> …. as soon as [other informants] start talking about embodied energy, you can rest assured that they've missed the point. Because it's not really about embodied energy, it's about a system and how its overall objectives are achieved.

Similarly, a member of the Canadian Standards Association (CSA) pointed out that 80% of energy use occurs during the operations phase of an infrastructure project, and not its planning, design, or construction phases (interview, CSA, 2013). Such comments illustrate that the integration of climate change necessarily entails more than a simple change to physical form and function (e.g. resource efficiencies in construction). As much of the literature stresses (e.g. Monstadt, 2009; Bulkeley *et al.*, 2013), the physical artefact is only one element in a complex system, and much of that system becomes evident only in use.

As an inter-dependent system, transport infrastructure involves more than a series of physical functions (e.g. getting from A to B). Rather, it involves the delivery of various services, from social care through emergency services (e.g. road use by emergency vehicles). A Toronto official explained:

> ... we've recognized the interdependency of infrastructure and we've done a whole study on identifying basic core functions that are necessary for maintaining the city of Toronto. And these core functions, they're not infrastructure, but they're actually services to people.

Nevertheless, materiality remains central to this analysis of transport infrastructure since services are still dependent on the systemic and material functioning of transport infrastructure.

Informants emphasized the importance of things like passive design and smart systems when it came to integrating climate change into infrastructure development. By this, the informants meant innovations that incorporate 'natural' systems into planning, design, and construction. As one engineer put it:

> ... how do we design the stations to integrate sustainability, how do we design the stations so that we can use natural processes for heating and for cooling? So, all that went into the design.

Another put it in a similar fashion:

> [In a subway station] you don't need air conditioning and you know we don't air condition our stations, so that will be something naturally, you know, that [uses] less power consumption and yet you give a better environment to the public or the passengers or the commuters.

Other examples of the integration of natural systems included planning that is focused on 'low impact development techniques, and this is all about managing storm water' (Ministry of Municipal Affairs and Housing 1, 2013); design that is 'very cognisant of sun, wind, other elements in the locating of buildings' (Planning 1 and Planning 2, 2013); construction that introduces air-conditioning 'through airflow and the piston effect essentially from the subways' (Construction 6, 2013); and things like 'natural lighting', 'natural heating', and 'permeable paving' (Construction 2, 2013). All these examples reflect the materiality of transport infrastructure and not necessarily socio-technical relations; critically, these materialities are very much implicated in the operation and function of the infrastructure as an inter-dependent or networked system, as mentioned above (Graham and Marvin, 2001; Bulkeley *et al.*, 2011).

Finally, infrastructure innovation is bound up with both these social and material elements of infrastructure as a socio-material system. It is important to stress the analytical, and practical, importance of materialities to infrastructure innovation because they are hardly covered in the literature at present (e.g. Geels, 2002; *cf.* Furlong, 2010). As Mitchell (2011) argues, these materialities are deeply political in that they both enable and constrain particular forms of social, political, and economic action (see Birch and Calvert, 2015). For example, planning can encourage or discourage physical density (e.g. suburb versus high rise). This density has direct implications for the political viability of certain transit systems (e.g. ridership numbers), which then reinforces the former planning decisions (e.g. lack of public transit is likely to reinforce mobility needs for cars, which then reinforces social preferences for suburban living). These materialities could be defined as the landscape of innovation, as with the MLP model (e.g. Geels, 2004). However, they represent more than the context in which sustainability transitions happen.

These materialities are an integral part of sustainability transitions, shaping their very possibility and the parameters in which they can happen. Moreover, they involve contestable decisions and choices. For example, a shift from planning, designing, and constructing road infrastructure to public transit infrastructure is a major and contested societal challenge.

Infrastructure innovation in Ontario

Informants highlighted the various ways in which climate change is integrated in the (1) planning and design, (2) construction, and (3) renewal stages of transport infrastructure developments. First, climate change is integrated at the planning and design stage through things like environmental impact assessments (EIA). EIAs illustrate how planning and design are inherently political processes that do not fit neatly into the MLP framework (e.g. Geels, 2002). More specifically, planning and design are broader than a *single* socio-technical regime. Indeed, they demonstrate the need to incorporate better the political (or power) processes in the analysis of sustainability transitions, as highlighted by several academics (e.g. Shove and Walker, 2007; Monstadt, 2009; Bulkeley *et al.*, 2013; Tyfield, 2014). For example, in Toronto, the environmental impacts of climate change (e.g. flooding) are used to lend political legitimacy to new forms of planning and design. In this sense, the bio-physical materialities at work provide the opening for the introduction of new social and technical components into the regime itself. For example, an Engineers Canada representative pointed out that there are a number of new or emerging assessment tools created by diverse stakeholders across Canada:

> We've had lots of flooding of course ... So sewer backups cause huge issues there and the insurance industry has developed a tool, a municipal risk assessment tool that assesses the risks of sewer backup ... most provinces have a climate change action plan at the provincial level and then that goes down into the municipal, local action plans.

Other informants also highlight that planning and design are still driven largely by broad socio-technical considerations, including established building code requirements and EIAs that have an impact on a range of regimes. For example, one engineer suggested that:

> ... the preliminary design or ultimate design has to be by legislation, acknowledge those and incorporate or address them or mitigate those concerns within the design. So, inasmuch as that process has been set up, it's a way in which to try to influence the design in accordance to what implications on climate change it could have.

Consequently, it is important to keep the broad socio-technical issues in sight in any analysis. In this sense, and as Tyfield (2014) argues, some socio-technical considerations are better thought of, analytically speaking at least, as part of the landscape; that is, the broader social, political, and economic pressures that condition a specific socio-technical regime. The reason for this is that legislation, codes, and standards are often both drivers and barriers to integrating climate change in infrastructure.

Second, while climate change is integrated at the planning and design stage, there are numerous examples of how it is integrated in the construction stage as well. Informants offered a number of specific examples including larger runoff; culvert and sewer systems to cope with increased and extreme precipitation; traffic signaling with electronic controller boxes to avoid over-heating; new asphalt mixes designed to tolerate heat and cold; material recycling (e.g. asphalt, steel, wood); permeable surfaces; 'green infrastructure' such as tree planting, green roofs and bioswales to reduce heat island effects; increased water absorption to avoid dangerous water runoff; and natural ventilation, lighting, and heating in buildings. These examples could reflect the innovation niches conceptualized by Geels (2002, 2004) and others, since they affect specific regimes.

Informants also highlighted generic examples of integration, such as 'adaptive' and 'resilient' infrastructure and planning. By adaptability and resilience, informants meant a number of things. On the one hand, some stressed the importance of connecting and integrating future planning needs and infrastructure construction:

> One of the other things that goes along with that is they're also designed to support future development around them. So, there's been that connection between design and planning ... the design of sort of the plazas or the access to the station or they're suited to a future development road network or development plan.

Socio-material systems, such as transport infrastructure, are inter-dependent systems (e.g. Frantzeskaki and Loorbach, 2010). Transport infrastructure is designed and constructed to suit the social needs of users. On the other hand, several informants reflected on the interplay among social, technical, and material elements in future planning and construction. They suggested that planning is largely guesswork (in that no-one *knows* (or discovers) where future demand for public transit will be) and that construction decisions and choices actually help to shape that future demand through the 'retrofitting' of cities. In this sense, such socio-material systems as transport infrastructure configure future decisions (e.g. travel routes) as much as they are configured by socio-technical knowledge and decisions (e.g. demand predictions and estimates). As one design engineer put it:

> So, on these sorts of projects you get not just into an element of, you know, pure ... shall we say transit design in just the pure sense. As you come to larger projects, which are more about city building, right, and so then therefore we start looking a bit more strategically.
>
> And cities are dynamic and they're always evolving so again a lot of the decisions relate around to the maturity of a city because that sort of dictates somewhat the issues of serving versus shaping.

The point to be emphasized here is that integrating climate change at the construction stage is not simply a response to 'technical' planning knowledge, practices, and standards (such as ridership needs and existing demand in the case of transit infrastructure). Construction, which entails a set of socio-material choices and decisions, also involves the shaping and reshaping of socio-technical regimes *and* landscapes, whether intended or not. In relation to this point, other informants talked about the impacts of such things as 'transit oriented development', 'building higher densities', and 'intensification'. These sorts of findings illustrate why a number of sustainability transitions academics think it is critical to include geography in ongoing debates (e.g. Coenen *et al.*, 2012; Lawhon and Murphy, 2012; Truffer and Coenen, 2012; Calvert *et al.*, 2017).

Finally, the *renewal stage* is an increasingly important phase at which to integrate climate change, especially since so much transport infrastructure is in need of renewal or rebuilding in Canada and beyond (Corfee-Morlot *et al.,* 2012). As one engineer put it:

> Replacing like-for-like has future cost implications. Under-designing infrastructure can result in the accelerated deterioration or failure of the infrastructure [and] much higher future costs. We are setting up future generations with better assets that are more resilient to the impacts of climate change.

The emphasis here, notably, has been on adaptation and not mitigation. The drivers of this renewal in Ontario are twofold. First, state-led strategies focused on adaptation rather than mitigation, resulting in shifting responsibility downwards from national to provincial and municipal scales of government. The increasing importance of adaptation innovation was evident in new policy concerns and strategies undertaken at the local government level by public or quasi-public sector actors. An Engineers Canada official pointed out that adaptation is 'very much a local community based thing; it's not like mitigation'. Similarly, a Federation of Canadian Municipalities official noted that adaptation was important in 'the communities particularly that keep getting hit by similar events repeatedly', including 'extreme storm events, extreme rainfall events, the basement flooding'. Such events have become a major concern in Toronto, according to one official:

> Now there's a thing called the basement flooding program and the wet weather flow master plan. Those were undertaken because engineers and staff at Toronto Water perceived more frequent extreme weather and complaints from the public.

As a result, renewal and maintenance are increasingly important issues, especially when it comes to cost. This is evident in the fact that municipal policy-makers and others are focusing on developing risk assessment tools and asset management mechanisms to extend the lifespan of infrastructure rather than simply knocking it down and rebuilding. However, as Monstadt (2009, p.1932) warns, there is a risk that local governments have lost or will lose control over transport infrastructure development as the result of cost *and* market pressures; that is, declining budgets and increasing privatization of infrastructure development (Birch and Siemiatycki, 2016). Consequently, it is vital to consider how transport infrastructure innovation is shaped by market pressures, or private sector actors.

Second, market-led strategies focused on reducing rising insurance costs resulting from weather and climate events. Hence, one important private sector actor driving infrastructure innovation is the insurance industry, whether directly or indirectly (e.g. Sturm and Oh, 2010). Geels and Schot (2007) note the importance of considering a range of social actors in socio-technical landscapes, regimes, and niches, going beyond the usual policy-makers. In climate change, this includes the insurance industry. For example, an informant from the Insurance Board of Canada explained that climate change adaptation has become an important issue within the insurance industry because of rising insurance claims resulting from flooding and weather events. This informant also made clear that infrastructure innovation is hampered by certain factors:

> [Lack of response to climate change] is mostly related, is mostly systemic and financial; systemic in the lowest bidder process, which is, quite frankly in my perspective, is moronic. And the second component of it is financial; there's, you know, municipalities are strapped for funding and because of that they don't necessarily have as much money as they would like in order to perform the maintenance of their infrastructure and let alone the upgrades. So those are the two drivers that essentially stop significant integration of adaptation into the urban planning.

As a result of constraints on government, market-led pressures (such as rising insurance premiums) may prove to be the key drivers behind transport (and other) infrastructure innovation when it comes to renewal. However, this does not explain how these social actors fit within socio-material systems. On the one hand, 'regime actors' may be key players in the MLP approach (Geels and Schot, 2007). On the other hand, other non regime-specific social actors (such as the insurance industry) also play an important and more general role in driving or derailing sustainability transitions.

Barriers to infrastructure innovation

While there are examples of how climate change is being integrated in transport infrastructure in Ontario, it is still evident that infrastructure innovation and societal transitions remain contested, controversial, and uneven. For example, there are still numerous barriers to innovation in transport infrastructure. This paper examines three. First, cost, financing, and contracting issues; second, infrastructure life cycle issues; and third, the implications for engineers as a professional group of integrating climate change into infrastructure.

Several informants mentioned that cost, financing, and contracting are a major barrier to the integration of climate change in infrastructure. These are combined because they often overlap, according to the informants. Cost, financing, and contracting are integral components in a socio-technical regime (Geels, 2004). However, it is possible to think of them as 'landscape' pressures that cut across regimes and niches in infrastructure innovation. For example, government budgeting and contracting rules usually cover a range of socio-technical regimes, not just transport infrastructure. As Shove and Walker (2007) and Tyfield (2014) note, it is worth considering conflicts between social actors in socio-technical regimes, and between regime actors and landscape actors. These social actors often have very different objectives, resources, and competencies when it comes to making and implementing new decisions or new ideas. As a construction engineer put it:

> However, one of the most significant components of cost in a project is risk and the delineation of risk between parties on a contractual basis, and the delineation and separation of contracts where one person is responsible up to a certain line and then the next person's responsibility takes place past that, right. And often what it also does is it crosses borders of competencies.

Another engineer confirmed the point:

> If it's built into a contract, people will do it, such as the recycling programs that I was referring to earlier ... But until it's legislated, you won't see the private sector lead that, because it adds cost to a competitive marketplace and nobody will take that risk to do that.

Costs, financing, and contracting are embedded in broader societal and political concerns, such as the public's willingness to pay higher taxes, and societal narratives about climate change. As a result, the integration of climate change can be diluted as tasks and roles are subcontracted by one social actor to another down the chain of responsibility. Subcontractors were frequently unable to integrate climate change in their activities because they needed to save costs immediately, as opposed to thinking about cost savings over the life cycle of the transport infrastructure project. Consequently, where climate change is not built into contractual arrangements throughout the various development stages, it tends to be sidelined. As one engineer explained, this is often driven by budget decisions:

> … you're automatically setting yourself up for budgetary constraints because you can't do everything you'd love to do and we've had some very ambitious designs initially, so the challenge is to work within the budget you've got available.

Second, as suggested by the constraints imposed by costs, financing, and contracting, transport infrastructure life cycles – central to their materiality – present a number of barriers to the integration of climate change. These range from the political (e.g. the turnover of politicians and their political mandates) to the technical (e.g. how to construct specific codes and standards in the light of data uncertainty). Thinking about the lifespan and cycle of transport infrastructure (that is, as a physical artefact) means paying analytical attention to its materiality, to how its physical characteristics shape and are shaped by specific socio-technical relations (Mitchell, 2011). One example of this materiality relates to the financing of infrastructure projects. Since infrastructure projects last for such a long time, their costs can be capitalized, thereby spreading them over the infrastructure's lifetime. While not paying enormous sums upfront is critical in budgetary terms, it requires certain knowledge and practices. For example, assessment and management tools are needed to ensure proper maintenance and life cycle costing, which in turn raises a series of political issues. As one engineer put it:

> And of course taxpayers want to pay as little and get a big return right and so if you don't have electricity priced properly and you don't have storm water drainage priced properly and you don't have all these other impacts priced properly based on carbon footprint, it's going to get the wrong answer because they're priced in dollars.

This is an example of how political materialities represent a potential barrier to transport infrastructure innovation. Physical characteristics shape social and economic considerations which, in turn, shape its physical form (e.g. lifespan). In this scenario, the people who build the infrastructure do not necessarily benefit from its integration of climate change. Moreover, these benefits can be hard to define since the avoidance of impacts is the benefit sought.

Finally, the integration of climate change has serious and ongoing implications for engineers as a professional group, especially when it comes to adaptation. Although discussed in some depth elsewhere (Birch and Wudrich, 2015), it is still important to highlight the implications facing engineers as a significant barrier. To start with, it is clear that a majority of Canadian engineers feel their activities are already affected by climate change (CSA, 2012). However, as an Engineers Canada official noted:

> … it looks like we've got quite a lot of work to do still in raising awareness. In fact, it's not really even raising awareness. [Engineers] seem to be aware, they just don't have the tools at this stage of the game.

Despite a range of new assessment protocols, engineers lack the tools needed to alter workplace practices because codes and standards, for example, can take time to change and are frequently contested by private developers who want to maintain minimum standards. As a construction engineer put it:

> Building codes, you know, they always up the ante in terms of energy consumption and insulation values and so on. But in my opinion, it's not enough, and I think there's a huge lobby group out there of developers who want to deliver cheap buildings to the public and then what gets built is code minimum and that puts money in the developers' pockets.

There are significant conflicts between different social groups, and professional groups, such as engineers, are often caught between competing pressures. While Geels and Schot (2007) characterize professional associations as landscape actors, this misses the point: engineers are themselves subject to certain (exogenous) limits, currently and in the future. For example, engineers in Ontario are, legally and professionally, required to work to specific codes and standards which are often based on historical data that are increasingly useless in the light of uncertain, future climate change (see CSA, 2010), but potentially face future liability claims if they ignore climate change now.

Conclusion

This paper started by discussing a range of literature on socio-technical systems and sustainability transitions in order to speculate on the relevance of materialities to infrastructure innovation and development (Graham and Marvin, 2001; Mitchell, 2011; Birch and Calvert, 2015). In doing so, it highlighted a number of analytical and political issues. First, sustainability transitions, as political projects, are premised on finding ways to transition to low-carbon societies and economies. However, this necessitates avoiding carbon lock-in (Unruh, 2000), which happens through the embedding of fossil fuel dependence in infrastructure developments. What makes this transition so urgent is that societies must undertake this action now or end up with infrastructure that is unsuitable for the next century. Second, there is a real risk that new and rebuilt infrastructure developments will not integrate climate change, which means that any examination of these innovation processes necessitates an analytical and methodological approach that can examine current changes as they are happening. Here, the sustainability transitions literature has an analytical gap. Focusing on a particular professional group – engineers – and their role in three Ontario infrastructure projects at different points in the infrastructure life cycle made this gap evident. It showed how climate change is, or is not, being integrated in new developments.

Finally, the sustainability transitions literature builds on a long conceptual tradition stretching back to research on large, technological systems (Hughes, 1983). The subsequent incorporation of social components by the likes of Geels (2002) and others, while important, could be pushed further. In particular, the analytical debate would benefit from further engagement with the implications of materialities (Mitchell, 2011). Consequently, to theorize transport infrastructure as a socio-material system incorporates the materialities of the artefact itself, allowing study of how infrastructure innovation is shaped by, and also shapes, the physical characteristics of infrastructure.

This analysis raises a range of important political issues when it comes to attempts to find and promote societal transitions to a low-carbon future. It is vital to understand infrastructure as a socio-material system in order to address the implications of the materialities of infrastructure development. As Mitchell (2011) argues, these materialities provide the possibilities for, and limitations of, social action. This means that publics, policy-makers, civil society, and business have to think about the interplay between socio-technical relations and materialities in their decisions. For example, the discussion of contracting and sub-contracting illustrates the extent to which there is a disjuncture between social expectations around costs and the physical lifespan of infrastructure. On the one hand, there is limited public and political will to support infrastructure innovation when it comes to integrating climate change, which feeds its way into how infrastructure is constructed and then paid for. As a result, infrastructure is increasingly 'splintered' into distinct material artefacts (e.g. one road, one transit line) because costs can be assigned to individual projects (Graham and Marvin, 2001). This means that infrastructure innovation is limited to individual projects rather than a socio-material system. On the other hand, there is significant potential for discounting and capitalizing the cost of infrastructure innovation across its lifespan, incorporating cost savings from, say, reduced energy needs, as long as infrastructure is conceptualized as an integrated system in which increased savings in one area can be applied to increased costs in another. Crucially, climate change adaptation depends on this latter, systemic approach, where infrastructure innovation integrates the social, technical, *and* material in new designs, developments, and construction.

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