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“Resilience thinking” in transport planning

Judith Y. T. Wang
Associate Professor in Transport Engineering
School of Civil Engineering & Institute for Transport Studies
University of Leeds
United Kingdom
Email j.y.t.wang@leeds.ac.uk

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Abstract

Resilience has been discussed in ecology for over forty years. While some aspects of resilience have received attention in transport planning, there is no unified definition of resilience in transportation. To define resilience in transportation, I trace back to the origin of resilience in ecology with a view of revealing the essence of resilience thinking and its relevance to transport planning. Based on the fundamental concepts of engineering resilience and ecological resilience, I define “comprehensive resilience in transportation” as the quality that leads to recovery, reliability and sustainability. Observing that previous work in resilience analysis in transportation has focussed on addressing engineering resilience rather than ecological resilience, I conclude that transformability has been generally overlooked and needs to be incorporated in the analysis framework for comprehensive resilience in transportation.

Keywords: resilience; transport planning; recovery; reliability; sustainability

1 Introduction

Resilience is a trendy word but unlike sustainability, it does not have a unified definition. Resilience is universally considered to be important and in some ways, e.g. in planning strategies for climate adaptation, it might appear that resilience is replacing sustainability (Davoudi, 2012). Some aspects of resilience have received considerable attention in transport planning for over a decade. Yet, it is not clear what resilience means in transport planning.

In this paper, I will first trace back to the origin of resilience in ecology, with a view to understanding the essence of "resilience thinking". The similarities of an ecological system to a transportation system are then uncovered. Based on the principles of resilience in ecology, I define "comprehensive resilience in transportation". I then look at what has been done in terms of enhancing comprehensive resilience in transportation and more importantly what might have been overlooked. Finally, I recommend a new way of "resilience thinking" in transport planning.

2 Resilience in ecology

What is resilience?

Resilience is a concept in ecology first introduced by Holling as "a measure of the persistence of systems and their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables" (Holling, 1973, p.14).

It is important to note that, as Holling (1996) pointed out, there are two faces of resilience in ecology: "engineering resilience" and "ecological resilience". "Engineering resilience" focuses on "efficiency, constancy and predictability". This is the core of engineering design, i.e. a "fail-safe" design. On the other hand, "ecological resilience" focuses on "persistence, change and unpredictability". In this case, resilience is about the amount of change a system can take before it flips to an alternate stability domain. In other words, this refers to "safe-fail" designs with an evolutionary perspective (Holling, 1996, p.33).

What is "resilience thinking"?

Walker in his interview with McDonald, explained that three main concepts define "resilience thinking" (McDonald and Walker, 2007, p.85):

1. complex adaptive systems are self-organising;
2. these systems are non-linear in their trajectories of change; which leads to their potential for multiple stability regimes; and
3. systems go through adaptive cycles, cycles which describe a repeated process of growth, conservation, collapse and re-organisation.

Walker further explained the three aspects of resilience as follows:

1. *resilience* is defined as "the amount of change a system can undergo before it crosses a threshold and flips to an alternate stability regime of that system" (Holling, 1973);
2. *adaptability* is "the capacity of the system (including humans, who are a key part of adaptive capacity) to 'manage' that threshold, stay away from it or change its position on the controlling variable"; and

3. *transformability*, "which can sometimes be in conflict with the first two, is the capacity of the system to literally transform itself into a different kind of system."

3 Relevance of "resilience thinking" in ecology to transportation

Transportation system versus ecological system

Transportation is an important element in our everyday life. It enables movements of goods and people so that we can gain access to basic needs such as food and clothing; be able to get to work and earn a living; access services such as medical care and education; and be able to participate in social activities with communities. While the movements of goods and people are both important, the management systems of such movements are fundamentally different. The movements of goods are generally determined by the logistics behind their distribution systems while the movements of people are the results of our own decisions. This paper focuses on the latter, i.e. the movement of people.

Let us first look at the similarities between transportation systems and ecological systems. It is well known in transport economics that travel demand is a 'derived demand' in the sense that travelling is a means to an end rather than an end itself. We travel not for the sake of travelling, but rather as a means to participate in different activities at different locations at different times. Thus any observed travel demand pattern is the result of our choices of where to live, where to work and how to travel.

While the decisions on how we travel can vary day-by-day, the decisions on where we live and where we work are longer term decisions. Thus the urban form of a city and its transportation system would naturally evolve over time as a result of the evolution of the decisions made by the inhabitants on where they live and work, as well as the policy makers' decisions on urban development and transport investments. It follows that transportation and land use systems are inextricably linked.

In my view, as part of an urban system, a land use and transportation system is similar to an ecological system in two respects:

1. a land use & transportation system is self-organising and adaptive; and
2. humans are a key part of adaptive capacity of the system because they are the objects of movements in the system. They have to contribute their precious time and energy to make the trips happen.

Land use & transportation system as a complex system

The complexity of the system can be reflected in the way that it is modelled. The interactions between land use and transport are well recognised in theory and in practice. Thus, location and transport choices are modelled with an integrated land use and transport planning approach. As an example, let us look at the Auckland Transport Models (ATM2) (Davies *et al.*, 2009; Feldman *et al.*, 2009), as illustrated in Figure 1.

The interactions between land use and transport decisions are modelled by the exchange of information between the two models, as demonstrated in Figure 1. The general idea is that personal travel demand is a 'derived demand'. To model travel demand, we will need to start with the land use pattern.

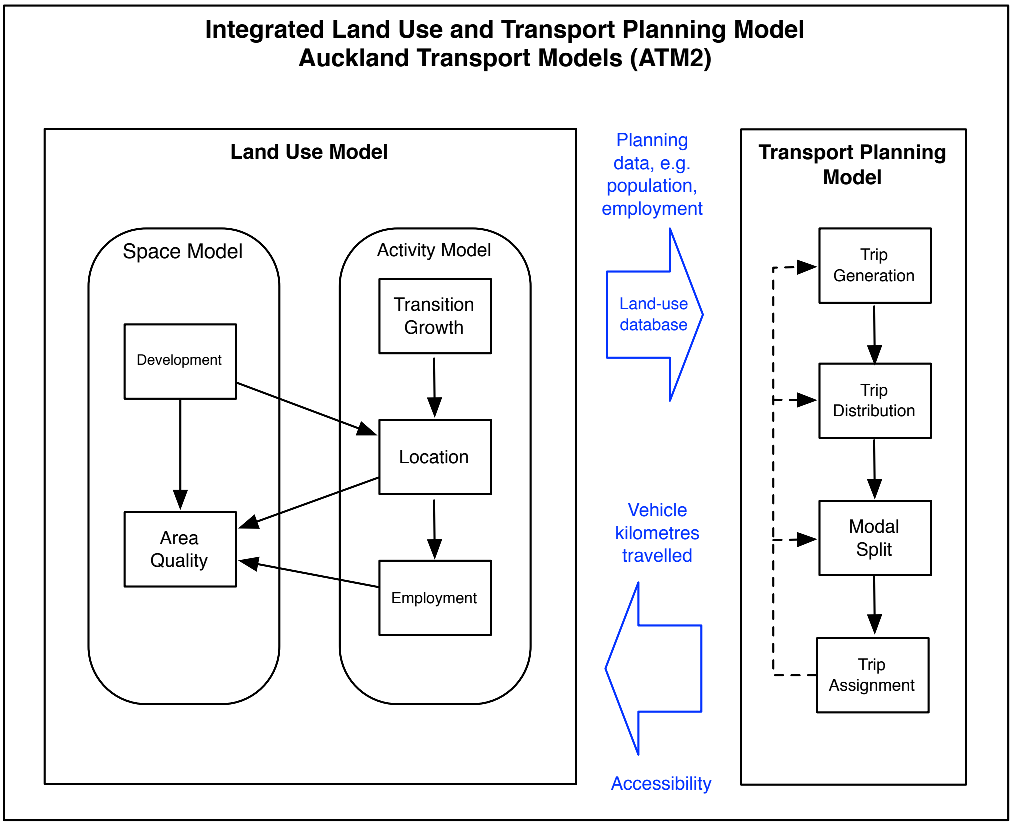


Figure 1: Integrated land use and transport planning model (drawn based on Simmonds (1999); Ortuzar and Willumsen (2001)).

The land use model component, as shown in Figure 1, consists of two sets of models: the Space models and the Activity models (Simmonds, 1999). The Space models include two sub-components: (1) the development model to predict the private-sector development process, i.e. where developers might like to build and the quantity of development; and (2) the area-quality model assumes that the inhabitants or users of an area have an influence upon its characteristics which, over time, affects its quality as a place to live or work. The Activity models include three sub-components: (1) the transition/growth component deals with the processes of change in the population, and the growth or decline in employment; (2) the location model predicts the location of households and employment, taking into account changes in accessibility, transport-related changes in the local environment, area quality, and the rent of space; and (3) the employment model deals with the changes in the demand for labour and the employment status of households as a result.

The transport model component, as shown in Figure 1, takes the land use data, i.e. population and employment size and locations as input to a four-stage transport planning model (Ortuzar and Willumsen, 2001): (1) trip generation involves determining the numbers of trips expected to leave each zone and to arrive in each zone; (2) trip distribution calculates the number of trips between zones; (3) modal split determines the number of trips by the different modes of transport available; and (4) trip assignment predicts the paths the trips will take. As a result of transport choices made, the resulting use of different transport modes will affect the generalised cost of travel, spatial distribution of the levels of congestion and hence the environment. The effects are modelled with accessibility and vehicle-kilometres travelled as proxy variables, which become input to the land use choices in the next period.

From the above, it is clear that a land use & transportation system is a complex system, as the two components interact with each other and their interactions evolve over time.

Land use & transportation system as an adaptive self-organising system

Metz (2008) looked at the average travel time (per person per year) in Britain reported since 1972/73 from the National Travel Survey (NTS) as well as reviews by others. Based on statistics from the 30-year period, Metz observed that, "in broad terms, average travel time holds constant across populations and over time at around 1.0–1.1 hours per day." One would expect that the land use pattern and transportation system must have changed over a 30-year period but clearly the average travel time has not. It appears that the improvement in technology and infrastructure has enabled the coverage of longer distances with a higher speed, which in turn enhanced access. Higher speeds on the journey to work have also enabled a greater choice of residence. Metz suggests that it seems more appropriate to assume that travellers aim to maximise access (rather than minimise travel time or generalised cost), subject to time and money constraints.

I see this as clear evidence of a land use & transportation system being an adaptive self-organising system. People choose where to live, where to work and how to travel. The resulting land use pattern and transport choices are the results of an adaptive self-organising process.

4 Resilience in transportation

Disruptions to a transportation system

We can characterise disruptions to a transportation system in two dimensions: frequency of occurrence and level of damage. In this way, as illustrated in Figure 2, disruptions to a transportation system can be classified into three categories: disasters, day-to-day variations to demand or capacity and ongoing long-term changes happening in the background. Disasters do not happen often but when they do, they may cause severe damage to the system, which can take a very long time to recover. Incidents such as traffic accidents, road works or increase in demand after school holidays can happen quite often and create variations in system capacity and demand. As a result, the system performance varies on a day-to-day basis. There are also disruptions happening in the background that might not be noticeable in the short term but that affect us on an ongoing basis. For example, the deterioration of air quality due to the increase in tailpipe emissions from motorists can have negative impact on public health.

To respond to these three categories of disruptions, a resilient transportation system must have the qualities (1) to recover efficiently from disasters; (2) to be reliable in terms of network connectivity and travel time reliability; and (3) to be economically, environmentally and socially sustainable. Note that following the concepts of "resilience thinking", here *recovery* includes both the possibilities of the system to return to *normal*, i.e. pre-disaster condition, and alternatively, to be rebuilt or transformed to a completely different system.

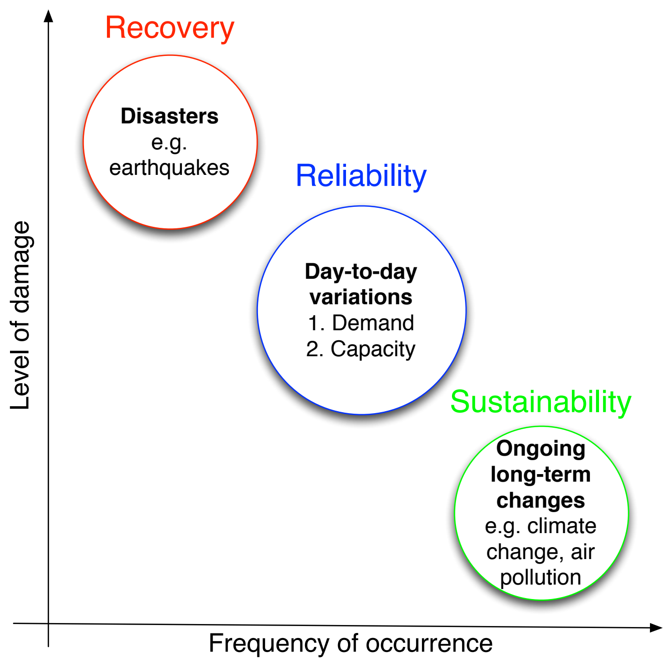


Figure 2: Classification of disruptions to a transportation system

Comprehensive resilience in transportation

Since Holling defined resilience in 1973, other concepts in ecology have emerged such as vulnerability and adaptive capacity, which have linkages to resilience in many different ways (Cutter *et al.*, 2008). For instance, Cutter *et al.* defined vulnerability as, "the pre-event, inherent characteristics or qualities of social systems that create the potential for harm." Adaptive capacity is defined in the literature as "the ability of a system to adjust to change, moderate the effects, and cope with a disturbance" (see e.g. Brooks *et al.*, 2005; Burton *et al.*, 2002). In my view, based on Holling's definition, resilience is above all what we would like to have in any system. Vulnerability can be viewed as characteristics of the system on the negative side of resilience while adaptive capacity is on the positive side. For example, health is obviously something everyone would like to have. To measure how healthy we are (resilience), we will need to measure how likely we might get sick (vulnerability), and how quickly we can recover in case we get sick (adaptive capacity). In order to assess how resilient an ecosystem or a transportation system is, we will need to be able to measure both the positive (adaptive capacity) and the negative (vulnerability) characteristics of the system. In order to improve resilience of a transportation system, we must have a plan that can reduce vulnerability and increase adaptive capacity of the system so that we can achieve comprehensive resilience. Here I define "comprehensive resilience in transportation" as the quality that leads to "recovery, reliability and sustainability" as illustrated in Figure 3.

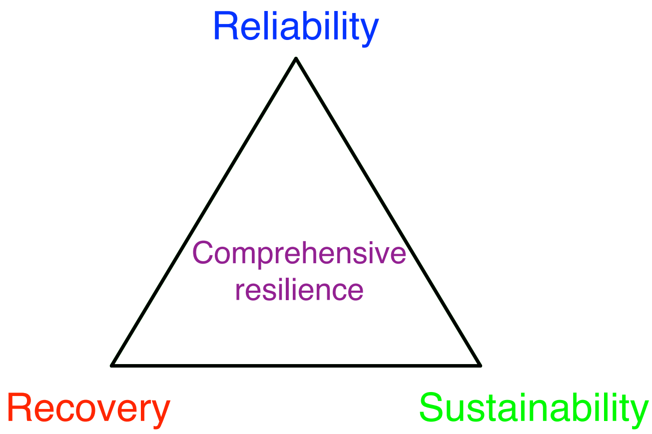


Figure 3: Comprehensive resilience in transportation

5 Resilience analysis frameworks in transportation

As mentioned earlier, there is no unified definition of resilience in transportation. I found that the current views on resilience generally follow Holling's definition of "engineering resilience", i.e. they are about "fail-safe" designs rather than "safe-fail" designs. As a result, the literature on assessing resilience in transportation has covered only two aspects of comprehensive resilience: recovery and reliability.

Let us first look at the analysis as related to road networks, which has been generally called *vulnerability* analysis. Berdica (2002) suggested that vulnerability analysis of road networks should cover four aspects, as depicted in Figure 4: (1) robustness – the ability of a system to withstand strain; (2) resilience – the maximum disturbance from which the system can recover and the speed of recovery (Goldberg, 1975); (3) redundancy – the existence of numerous optional routes/means of transport between origins and destinations, which can result in less serious consequences in case of a disturbance in some part of the system; and (4) reliability – adequate *serviceability* under the operating conditions encountered during a given period.

Berdica (2002) further elaborated that reliability covers three main aspects in the literature: (1) reliability of connectivity – the probability of reaching a chosen destination at all (Bell and Iida, 1997); (2) reliability of travel time – the probability of reaching a chosen destination within a given time (Bell and Iida, 1997); and (3) capacity reliability – the probability of the network being able to absorb a certain amount of traffic within an acceptable level of service, e.g. Chen *et al.* (1999, 2013).

It is important to note that Berdica (2002) did mention that, "Resilience could also be described as the capability of reaching a new state of equilibrium. However, many of the incidents causing reductions in serviceability have a relatively short duration, never reaching a new equilibrium. This so called transient state still remains to be studied/modelled more thoroughly." In other words, what Berdica considered as resilience is associated with Holling's definition of "engineering

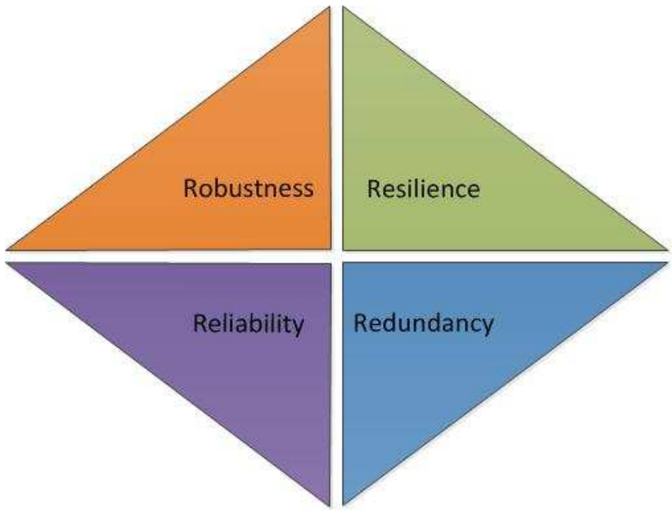


Figure 4: Four aspects of road vulnerability analysis, drawn based on Berdica (2002)

resilience", which is a short-term measure of resilience rather than a long-term one.

Since Berdica's review, extensive research has emerged on resilience analysis in relation to the aspects identified in Berdica's paper (see e.g. Jenelius *et al.*, 2006; Serulle *et al.*, 2011; Freckleton *et al.*, 2012; Balijepalli and Oppong, 2014; Jenelius and Mattsson, 2014). Yet they all address "engineering resilience" rather than a complete picture of resilience.

Let us look at the latest paper of Jenelius and Mattsson (2014) in more detail as an example. Jenelius and Mattsson defined road network vulnerability analysis as "the study of potential degradations of the road transport system and their impacts on society, modelling the road infrastructure as a network with links (road segments) and nodes (intersections)". Jenelius and Mattsson assessed the impacts of disruption scenarios for individuals, evaluated in economic terms in two perspectives: (1) *users* – how different user groups are affected under various disruption scenarios; and (2) *road network* – how disruptions of different network elements affect the user and society overall.

The measures of impact, expressed as *exposure* and *vulnerability*, were further developed based on concepts in Jenelius *et al.* (2006): (1) *exposure* – the impact for a single user under a certain disruption scenario is referred to as the *exposure* of the user to that scenario; and (2) *vulnerability* – combining the exposure with the probability of the scenario gives the *vulnerability* of the user to that scenario. Jenelius and Mattsson's work focussed on the spatial and socioeconomic impact. The idea is to study and compare the situation for different individuals depending on the socioeconomic, demographic and geographic variables of interest.

Concerning public transport network resilience analysis, Cadarso *et al.* (2013) looked at large-scale disruption problems of rapid transit railway systems. They proposed an integrated optimisation method for the timetable as well as the rolling stock, taking into account passengers' behavioural change during disruptions. Jin *et al.* (2014) performed network disruption analysis for public transport networks. Jin *et al.*'s model was developed based on concepts from freight networks (Chen and Miller-Hooks, 2012; Miller-Hooks *et al.*, 2012), where an indicator of network resilience is defined as the ability of an intermodal freight transport network to recover from natural or human-caused disruptions. They defined the resilience of a metro network as the fraction of travel demand that can be satisfied by the degraded metro network after disruptions. They applied this method to assess the resilience of metro networks and propose integration adjustments between bus services and metro to enhance the resilience of the integrated metro-bus system.

Rodriguez-Nunez and Garcia-Palomares (2014) proposed a method to analyse public transport network vulnerability by measuring the impact in terms of disruptions of riding times or number of trips missed.

As shown above, road vulnerability analysis and resilience analysis for public transport networks in the literature have been built to facilitate the efficiency of the system to go back to *normal* after disruptions. What I would like to illustrate here is that the current form of "resilience" analysis by default means "engineering resilience" according to Holling's definition. "Resilience thinking" as in ecology has not been applied in transport planning at all in a comprehensive manner.

6 Sustainability analysis frameworks in transportation

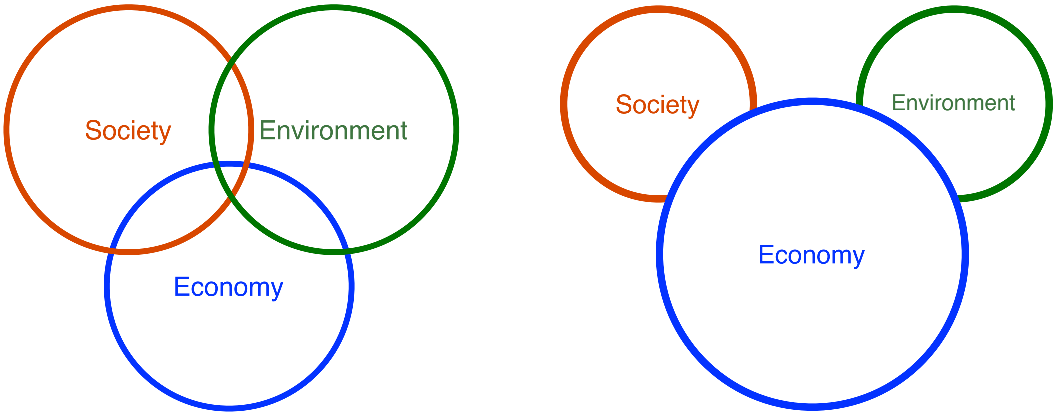
Now let us look at the third aspect of "comprehensive resilience in transportation", i.e. sustainability. The concept of sustainability is defined in the report of the United Nation World Commission on Environment and Development (1987) (Brundtland Report) as meeting the needs of the present without compromising the ability of future generations to meet their own needs. This leads to what is often referred to as the "three-legged stool" (or the triple bottom-line model) of sustainability: economic, environmental and social sustainability (European Commission, 2004), as illustrated in Figure 5(a).

Since the introduction of the sustainability concept, the use of indicators for performance measurement and management in the transport sector has received strong emphasis, particularly in Europe, e.g. Walker *et al.* (2006); Marsden *et al.* (2010); Marsden and Snell (2009). In the U.K., all local authorities are now required to set out five-year programs with commitments on progress over a range of mandatory and voluntary indicators (Marsden *et al.*, 2006). Research in the U.K. found that there are too many indicators and yet too little clarity about what is collected and reported on, at what level, and why. Marsden *et al.* (2006) concluded that the lack of a comprehensive framework increases the risk of negative impacts from monitoring programs.

Sustainable Aotearoa New Zealand Inc. (2009) highlighted another danger that might occur when applying the idealised triple bottom-line model as illustrated in Figure 5(a). This model assumes an appropriate balance between economic, environmental and social outcomes, which is usually not the case. At its worst, economic outcomes dominate, and environmental and social outcomes receive minimal attention. This then becomes the "Mickey Mouse model" as shown in Figure 5(b).

In most developed countries (e.g. UK, New Zealand) transport investment decisions are justified by standard economic evaluation procedures, in which the value of travel time savings plays a key role in cost-benefit analysis (CBA) (Mackie *et al.*, 2001; Grant-Muller *et al.*, 2001). The general principle behind CBA is to consider the potential costs and benefits of a particular project across a set of impacts, including environmental and socio-economic impacts. The impacts are then translated into monetary terms by multiplying impact units by prices per unit. However, not all environmental and socio-economic impacts are considered and can be monetarised. Some of them are instead quantified into their own measurable units or assessed on a qualitative basis (Grant-Muller *et al.*, 2001). In the UK, for example, travel time savings account for around 80% of the monetarised benefits within the CBA of major road schemes (Metz, 2008). However, as discussed earlier, there is little empirical evidence to support whether there is travel time saving at all (Metz, 2008).

I see this as a "Mickey Mouse" effect created by applying standard economic evaluation procedures. The benefits measured by travel time savings have been amplified because travel time is something easy to measure, while some aspects of environmental and social impacts might not be quantifiable at all. Then we end up focussing on what we can measure, which might not



(a) The triple bottom-line model (b) The 'Mickey Mouse' model

Figure 5: The triple bottom-line model vs The "Mickey Mouse" model, adapted from Sustainable Aotearoa New Zealand Inc. (2009)

be the most important. The economic evaluation procedures do not reflect the importance of environmental and socio-economic benefits, as they are meant to be, namely on an equal basis.

7 Discussion

Consequences of focussing only on "engineering resilience"

While enhancing "engineering resilience" is important, there might be a price to be paid for focussing only on it. As Walker suggested, "while you are building up resistance, you may be decreasing resilience." (McDonald and Walker, 2007, p.90)

For instance, according to the principles that we discussed earlier in Section 5 (Berdica, 2002; Jenelius and Mattsson, 2014), to enhance resilience of road networks, we need to provide enough alternative routes for all destinations. The redundancy of routes is important under emergency situations but at the same time, the provision of additional road capacities might also promote road-oriented development. As a result, this might lead to urban sprawl and higher car dependency. People drive for longer distances at higher speeds (Metz, 2008). They might be happier in the short term because they can enjoy the lifestyle that they wanted. Yet in the long run, they might suffer the long-term effect of lack of physical exercise, the stress from being stuck in traffic, etc. Damage caused by the emissions to the environment during their long distance commute is also inevitable, which in turn might cause health problems to themselves due to the effect of deterioration of air quality, especially during their commute journeys. Thus, a focus on improving "engineering resilience" might cause a reduction of resilience of the system in terms of the health and fitness of humans.

Research has shown that there is a strong relationship between our transportation system and public health (Woodcock *et al.*, 2009; Litman, 2013). As highlighted earlier in Section 3, humans are a key part of adaptive capacity of a transportation system. However, it appears that this has not yet been considered under the existing analysis frameworks of resilience in transportation.

Incorporating "transformability" in "comprehensive resilience in transportation"

Now let us revisit the concepts of resilience in ecology in Section 2. As explained by Walker, "We can make the system that we *like* persist over a long period. And if the system that we define socially is not going to survive like that, then we have to, in advance, transform ourselves. And the sooner we do it, while we are still in control, the less will be the costs and pain." (McDonald and Walker, 2007, p.91) Walker also highlighted the importance of maintaining diversity as a key to survival. In ecology, resilience is not just about the capability of the system to get back to what is considered as *normal* after disruptions, but also about the capability to be able to *transform* when it becomes impossible to get back to *normal*.

Applying this concept in transport planning, let us consider, for example, the situation where the majority of the population driving to work is considered to be *normal*. Now if we imagine a worst case scenario where fossil fuels have run out, then for those who normally drive to work, life might never be able to get back to *normal* again. On the contrary, for those who normally bike or walk to work, life would remain *normal*. For those who take public transport, life might or might not have changed, depending on the sources of energy for the public transport system. Obviously, a multi-modal transportation system with *diversity*, i.e. a wide variety of mode and route choices, would be a more resilient system as compared with a car-dominated system. If everyone owns a bike and is fit enough to ride, then even when there is no petrol, the system can still function, at least partially, because it can be easily transformed to a bike-and-walk system.

In ecology, transformability becomes very important when a system is in a stability regime that is considered undesirable, and it is either impossible, or getting progressively harder and harder, to engineer a 'flip' to the original or some other stability regime of that same system (McDonald and Walker, 2007, p.86). In transport planning, I consider that "transformability" is central to "comprehensive resilience in transportation", as demonstrated in Figure 6, which is a perspective that has been overlooked in resilience analysis.

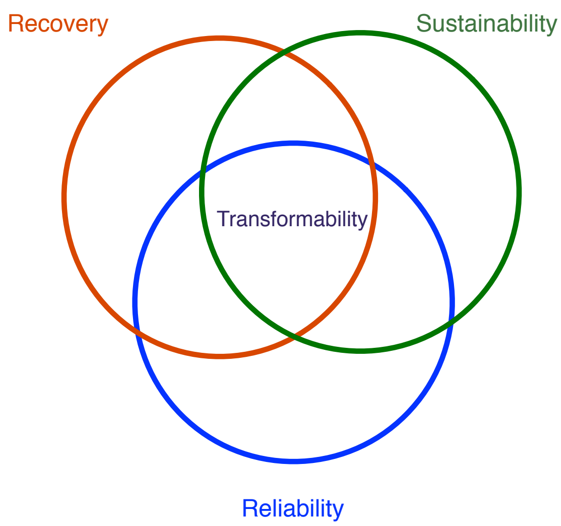


Figure 6: Incorporating "transformability" in "comprehensive resilience in transportation"

8 Conclusion

In this paper, in order to elucidate the importance of resilience to transport planning, I traced back to the origin of resilience in ecology with a view of revealing the essence of "resilience thinking". I demonstrated the similarities between ecological and transportation systems, in the sense that they are both complex, adaptive and self-organising. By applying the concepts of resilience in ecology, I then defined "comprehensive resilience in transportation" as the quality that leads to "recovery, reliability and sustainability". There are two faces of resilience in ecology: engineering resilience and ecological resilience. It appears that resilience in transportation by default is associated with engineering resilience, i.e. resilience analysis in transportation in the literature has mostly covered recovery and reliability. In particular, a lot of research effort has been looking into recovery to pre-disaster condition rather than taking a disaster as an opportunity to rebuild or transform a system into a completely different system with a more desirable equilibrium state. Focussing mostly on engineering resilience imposes the danger of reducing the resilience of the system in other aspects, such as human health, by not improving the diversity of adaptive capacities of the system or transformability. Finally, I recommend that we must incorporate transformability in our analysis framework in order to achieve "comprehensive resilience in transportation".

References

Balijepalli, C. and Oppong, O. (2014). Measuring vulnerability of road network considering the extent of serviceability of critical road links in urban areas. *Journal of Transport Geography*, **39**, 145–155.

Bell, M. G. H. and Iida, Y. (1997). *Transportation network analysis*. John Wiley & Sons.

Berdica, K. (2002). An introduction to road vulnerability: What has been done, is done and should be done. *Transport Policy*, **9**(2), 117–127.

Brooks, N., Adger, W., and Kelly, P. (2005). The determinants of vulnerability and adaptive capacity at the national level and the implications for adaptation. *Global Environmental Change*, **15**(2), 151–163.

Burton, I., Huq, S., Lim, B., Pilifosova, O., and Schipper, E. (2002). From impacts assessment to adaptation priorities: The shaping of adaptation policy. *Climate Policy*, **2**(2-3), 145–159.

Cadarso, L., Marn, A., and Maroti, G. (2013). Recovery of disruptions in rapid transit networks. *Transportation Research Part E: Logistics and Transportation Review*, **53**(1), 15–33.

Chen, A., Yang, H., Lo, H. K., and Tang, W. H. (1999). Capacity related reliability for transportation networks. *Journal of Advanced Transportation*, **33**(2), 183–200.

Chen, A., Kasikitwiwat, P., and Yang, C. (2013). Alternate capacity reliability measures for transportation networks. *Journal of Advanced Transportation*, **47**(1), 79–104.

Chen, L. and Miller-Hooks, E. (2012). Resilience: An indicator of recovery capability in intermodal freight transport. *Transportation Science*, **46**(1), 109–123.

Cutter, S., Barnes, L., Berry, M., Burton, C., Evans, E., Tate, E., and Webb, J. (2008). A place-based model for understanding community resilience to natural disasters. *Global Environmental Change*, **18**(4), 598–606.

Davies, J., Valero, J., and Young, D. (2009). The Auckland Transport Models project: Overview and use to date. In *The 32nd Australasian Transport Research Forum, Auckland, New Zealand, September 2009*.

Davoudi, S. (2012). Resilience: A bridging concept or a dead end? *Planning Theory and Practice*, **13**(2), 299–307.

European Commission (2004). *Planning and Research of policies for land use and transport for increasing urban sustainablity PROPOLIS: Final Report to European Commission*. European Commission, Brussels, Belgium.

Feldman, O., Davies, J., Simmonds, D., Young, D., Richmond, E., and Valero, J. (2009). An integrated system of transport and land-use models for Auckland and its application. In *The 32nd Australasian Transport Research Forum, Auckland, New Zealand, September 2009*.

Freckleton, D., Heaslip, K., Louisell, W., and Collura, J. (2012). Evaluation of resiliency of transportation networks after disasters. *Transportation Research Record*, **2284**, 109–116.

Goldberg, M. A. (1975). On the efficiency of being efficient. *Environment and Planning A*, **7**, 921–939.

Grant-Muller, S., Mackie, P., Nellthorp, J., and Pearman, A. (2001). Economic appraisal of european transport projects: The state-of-the-art revisited. *Transport Reviews*, **21**(2), 237–261.

Holling, C. S. (1973). Resilience and stability for ecological systems. *Annual Review of Ecology and Systematics*, **4**, 1–23.

Holling, C. S. (1996). *Engineering within ecological constraints*, chapter Engineering resilience versus ecological resilience, pages 31–44. National Academy Press.

Jenelius, E. and Mattsson, L.-G. (2014). Road network vulnerability analysis: Conceptualization, implementation and application. *Computers, Environment and Urban Systems*. http://dx.doi.org/10.1016/j.compenvurbsys.2014.02.003.

Jenelius, E., Petersen, T., and Mattsson, L. G. (2006). Importance and exposure in road network vulnerability analysis. *Transportation Research Part A: Policy and Practice*, **40**(7), 537–560.

Jin, J. G., Tang, L. C., Sun, L., and Lee, D.-H. (2014). Enhancing metro network resilience via localized integration with bus services. *Transportation Research Part E: Logistics and Transportation Review*, **63**, 17–30.

Litman, T. (2013). Transportation and public health. *Annual Review of Public Health*, **34**, 217–233.

Mackie, P. J., Jara-Diaz, S., and Fowkes, A. S. (2001). The value of travel time savings in evaluation. *Transportation Research Part E: Logistics and Transportation Review*, **37**(2-3), 91–106.

Marsden, G. and Snell, C. (2009). The role of indicators, targets and monitoring in decision-support for transport. *European Journal of Transport and Infrastructure Research*, **9**(3), 219–236.

Marsden, G., Kelly, C., and Snell, C. (2006). Selecting indicators for strategic performance management. *Transportation Research Record*, **1956**, 21–29.

Marsden, G., Kimble, M., Nellthorp, J., and Kelly, C. (2010). Sustainability assessment: The definition deficit. *International Journal of Sustainable Transportation*, **4**(4), 189–211.

McDonald, T. and Walker, B. (2007). Resilience thinking: Interview with Brian Walker. *Ecological Management and Restoration*, **8**(2), 85–91.

Metz, D. (2008). The myth of travel time saving. *Transport Reviews*, **28**(3), 321–336.

Miller-Hooks, E., Zhang, X., and Faturechi, R. (2012). Measuring and maximizing resilience of freight transportation networks. *Computers and Operations Research*, **39**(7), 1633–1643.

Ortuzar, J. d. D. and Willumsen, L. G. (2001). *Modelling Transport*. John Wiley, 2nd edition.

Rodriguez-Nunez, E. and Garcia-Palomares, J. C. (2014). Measuring the vulnerability of public transport networks. *Journal of Transport Geography*, **35**, 50–63.

Serulle, N. U., Heaslip, K., Brady, B., Louisell, W. C., and Collura, J. (2011). Resiliency of transportation network of santo domingo, dominican republic: Case study. *Transportation Research Record*, **2234**, 22–30.

Simmonds, D. C. (1999). The design of the delta land-use modelling package. *Environment and Planning B: Planning and Design*, **26**, 665–685.

Sustainable Aotearoa New Zealand Inc. (2009). Strong sustainability for New Zealand: Principles and scenarios. New Zealand: Nakedize Limited. Available online `http://nz.phase2.org/strong-sustainability-for-new-zealand`. Retrieved 07/12/2014.

United Nation World Commission on Environment and Development (1987). Our common future: Report of the World Commission on Environment and Development. Available online at `http://www.un-documents.net/our-common-future.pdf`. Retrieved 25/01/2015.

Walker, W. E., Rahman, S. A., van Grol, R., and Klautzer, L. (2006). Commentary: Operationalizing the concept of sustainable transport and mobility. *Environmental Practice*, **8**(1), 24–48.

Woodcock, J., Edwards, P., Tonne, C., Armstrong, B. G., Ashiru, O., Banister, D., Beevers, S., Chalabi, Z., Chowdhury, Z., Cohen, A., Franco, O. H., Haines, A., Hickman, R., Lindsay, G., Mittal, I., Mohan, D., Tiwari, G., Woodward, A., and Roberts, I. (2009). Public health benefits of strategies to reduce greenhouse-gas emissions: urban land transport. *The Lancet*, **374**(9705), 1930–1943.