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Modelling the Costs of Unexpected Traffic Flow Disruptions

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Abstract

Cost-benefit analysis is a well-recognized assessment tool for evaluating transport infrastructure projects. However, existing frameworks do not fully consider the benefits for road users of reducing the frequency and duration of unexpected road closures. The aim of this paper is twofold. First, a model is developed to assess the economic consequences of weather-related disruptions causing road closures. Second, an application of the model is provided using empirical evidence from Norway. The benefits for road users of reducing the frequency and duration of temporary traffic flow disruptions can be extensive and should be considered in cost-benefit analysis of relevant infrastructure projects.

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1.0 Introduction

Transport operations in different regions of the world have been and are still affected by weather conditions in various ways, depending on geographical and climatic conditions. The road transport systems in regions with cold winter weather such as the Alps, the Snow Belt states in US, Arctic areas (see, for example, Streicker (2013) for definitions) and other mountainous regions are particularly challenged by adverse weather. The road surfaces are covered with snow and ice during winter, and wind and snow often creates difficult driving conditions by reducing sight and causing snow to block the roads. Among others, this increases the risk of accidents (Qiu & Nixon, 2008) and sometimes the roads are preventively closed because it is considered too dangerous for free movement of vehicles (Thomas H Maze, Crum, & Burchett, 2005; NPRA, 2012). These are examples of events that are characterized by being sudden and unexpected, and cause traffic flow disruptions. These disruptions are problematic for the people and businesses in various ways (Bardal, 2017). First, travel times increase when the road users need to either wait for the road to open or take longer detours. Second, the pecuniary costs increase if the road users choose or are forced to take detours, because vehicle operating costs may increase, and the detour may include ferry tickets or tolls. Since many of the areas affected by the types of disruptions mentioned above are rural with limited access to alternative transport routes and modes, detours may be particularly long and costly. Third, the unexpected nature of the disruptions makes the travel times unreliable, which implies further extra costs for the road users (for example, punishments for being late for appointments, necessity of including buffer time in their schedule etc.).

It is well documented in the literature that people are willing to pay for both travel-time savings and reliable travel times (see, for example, Bates et al., 2001; Li et al., 2010). Small (2012) and Abrantes and Wardman (2011) review the literature on the evaluation of travel time savings, while, for example, Carrion and Levinson (2012) and Li et al. (2010) review the literature on the valuation of travel time reliability.

However, while the literature on the value of travel time reliability is well-developed (see, for example, Fosgerau & Karlström, 2010), the existing frameworks for valuing travel-time savings and increase in pecuniary costs in the context of unexpected traffic flow disruptions are at an earlier development stage (for example, Jenelius & Mattsson, 2015). This paper adds to the latter literature. The knowledge developed has practical implications for economic impact assessment of future infrastructure projects since the benefits of reducing the economic loss due to increased travel times and pecuniary costs caused by unexpected traffic flow disruptions, are not fully included in economic impact assessment tools of infrastructure projects such as cost-benefit analyses (CBA). The result is assessment tools that do not disclose these important benefits for the road users.

The aim of this paper is twofold. First, the models found in existing literature on calculating the risk and costs of road closures due to avalanches and landslides are compiled and modified in order to develop a framework that can be applied to all kinds of weather-related road closures for use in cost-benefit analyses of infrastructure projects. Second, for illustration purpose, the developed framework is applied to two different types of disruptions on a specific stretch of road located in the northern part of Norway, namely preventive road closures due to adverse weather and road closures due to accidents. The region's topography is characterized by a long coastline with deep fjords and steep mountains. The rough weather conditions have always been a challenge for transport in this area. In fact, Meersman and Van De Vorde (2001) list preventive winter road closures in Norway as one of the barriers to interoperability in European transport. Research on climate change indicates that these kinds of problems are likely to increase in the future because of more-frequent and more-intense precipitation, increased wind, and more days with temperatures around 0°C in winters (NPRA, 2011a).

The model developed should be applicable to all kinds of road sections in rural areas experiencing sudden and unexpected traffic flow disruptions. A more sophisticated model would be necessary to fit urban areas in which there are more available alternative transport modes and routes, and more common with a wider variety of behaviour reactions to the traffic flow disruptions.

The paper is structured as follows: The model is presented in Chapter 2. Chapter 3 contains a description of the case and data used to illustrate the application of the model. The results from the analysis are presented and discussed in Chapter 4. Concluding remarks and implications are provided in Chapter 5.

2.0 The Model

2.1 Time Value and Time Reliability

The work of Becker (1965) was one of the earliest discussions of the role of time in consumer theory. Becker (1965) included the cost of time on the same footing as the cost of market goods, and thereby recognizing that consumption has a time cost. The traditional framework to model consumer behaviour assumes that individuals are trying to achieve the highest level of satisfaction given the constraints. The introduction of time in these models follows the need to understand the labour market as the consumer is assumed to face a choice between work and non-work time (Jara-Diaz, 2007).

Both revealed preference (RP) and stated preference (SP) experiments have been used to estimate individuals' willingness to pay (WTP) for travel time savings (Hensher, 2001). Extensive research conducted in various countries has produced estimates of the value of travel time in different contexts (Ho et al., 2016). Abrantes and Wardman (2011), Kato et al. (2010), Shires and de Jong (2009) and Zamparini and Reggiani (2007) are examples of meta-analyses on the value of travel time in the UK, Japan, and 30 countries globally. The literature reveals great heterogeneity in values of time depending on characteristics of the trip and the traveller (see, for example, Abrantes and Wardman, 2011; Börjesson and Eliasson, 2014; Small 2012).

The importance of reliable travel times is highly recognized in the literature, especially for passenger transport (see, for example, Asensio and Matas, 2008; Bates et al., 2001; Li et al., 2010; Sikka and Hanley, 2013). Studies show that travel time variability is often valued higher than travel time savings (for example, Asensio and Matas, 2008). Recently, the literature has emerged also on the reliability of travel times in freight transport (for example, de Jong et al., 2014; Halse et al., 2010).

Most reliability measures are calculated as the variability experienced on a route on a particular time-of-day and day-of-week during a longer period of time (van Lint et al. 2008). Various travel time reliability measures have been used, but the most common ones are the mean-variance/centrality-dispersion and the scheduling models according to Carrion and Levinson (2012), who have reviewed the literature on travel time reliability. The disutility of delays is often assumed to be proportional to the average delay (Börjesson and Eliasson, 2011). However, Börjesson and Eliasson (2011) found that the value of delays increases slower than linearly with frequency. Consequently, the literature has identified the importance of considering different aspects of travel time when evaluating transport activity. In the following sections we will establish a model framework to include the time valuation effects of unexpected delays in the traditional cost-benefit approach.

2.2 Economic Assessment of Infrastructure Disruptions

Disruptions may affect the infrastructure in many ways. According to InfraRisk (2013), the consequences for society of a specific incident will depend on its type, magnitude, extent, and how the infrastructure is affected. An incident may reduce both the physical and functional value of the infrastructure. Physical values relate to the cost of physical damage; while functional values relate to the utility gained by using the object (that is features that the object operate). Delay costs usually defined per traffic volume (for example, delay costs per vehicle per hour), takes the form of reduction in the functional value of the infrastructure.

When the functionality of the infrastructure is threatened, it is relevant to assess risk systematically. The definitions of the risk concept suggested in the literature is vast (Aven, 2012). Fell et al. (2005) define risk quantitatively as the "probability of an adverse event times the consequences if the event occurs". According to this definition, risk is understood as the expected value of the economic loss associated with an event (Aven, 2012). Both economic consequences and probability are incorporated in the term "risk". For cost-benefit analyses of risk-reducing investments, it is desirable to express the disruption impacts in economic terms. In line with the model by Fell (1994) addressing landslides, equation

(1) provides a general way of expressing the total risk, R, due to a disruption in the transport system.

$$R = H \cdot X \cdot G \tag{1}$$

In (1), the total risk, R, is the annual expected economic loss experienced by the road users on a specific section of road when disruptions cause the road to close. H represents hazard and is defined as the annual disruption frequency at the specific road section. X represents traffic volume affected by a road closure. The last element to the right in

(1), G, represents the vulnerability of the variable X and indicates the degree of loss to X. For functional values, G can be considered the cost component to be multiplied by X, implying that $G \geq 0$ (InfraRisk, 2013). For physical damages, G represents the proportion of X expected to be lost. Hence, $(X \cdot G)$ is the economic loss per disruption. For each type of incident potentially harmful to the infrastructure, there is a need to parameterize the variables by dividing G into several measures with separate valuations. Consequently, despite the use of general damage functions, there is a need for risk assessments to be case specific.

Jenelius and Mattsson (2015) conceptualize a model for assessing the expected impacts for society of system disruptions equivalent to parameter R in

(1). Our model builds on the reasoning by Jenelius and Mattsson (2015), but rather than dealing with the entire infrastructure network, one specific link is analysed in more detail in our model. The reason for this approach is that the aim is to assess the unexpected costs imposed on travellers (increase in generalized transport costs, G) by disruptions on a specific link as input in cost-benefit analysis (CBA). The considered disruptions consist of road closures for a certain duration, denoted q hours. The duration may vary between incidents from only a few hours for an accident to more than a day for preventive closure due to bad weather. The road section has a fixed length and thus a fixed travel time when there are no disruptions, denoted t. The unit of analysis is traffic volume, measured by the number of vehicles per hour, x. Hence, the total number of vehicles affected by a disruption with a duration of q hours is $X = x \cdot q$.

2.3 Model Assumptions

Due to common limitations of available traffic data, there is a need to impose some assumptions on traffic flow and driver behaviour. First, within a given timeframe it is assumed that traffic demand per hour (x) is constant during the disruption and that disruptions are randomly distributed across the time of the day. This assumption on demand is in line with Jenelius & Mattson (2015). The model will need to be adjusted in areas where the data on disruptions show clear patterns diverging substantially from this assumption. To consider variations in demand across the year, a given timeframe such as season, is considered. Second, the alternative routes have enough capacity to serve the traffic transferred from the disrupted road without considerable congestion effects. Evidently, this assumption is unrealistic in parts of the transport network with congestion problems or where scheduled services, such as car ferries have limited capacity. With respect to disruptions due to adverse weather conditions, it could be delays on detours as well since they are in the same region. Third, travellers have full information about available detour routes, both pecuniary costs and time-use related to each detour alternative. The increasing availability of on-line information sources and real-time flow of information due to technological advances, makes this assumption more likely to hold. In addition, the model assumes that the road users have information about the expected duration of the road closure. Although the duration of a road closure may be uncertain, the rescue teams and road operation teams will often be able to provide an estimated duration based on experience. The ability to predict when the road opens, may vary both with type of disruption and within each category of disruption. For example, the weather, causing preventive closures, may be more uncertain to predict than the time needed to clear the road after an accident.

Finally, a critical assumption regards the behaviour of people when trips cannot be made as planned. First, we develop a model assuming that the travellers either wait for the road to reopen or take a detour. This is in line with assumptions in current models (Bråthen, Husdal, & Rekdal, 2008; Jenelius & Mattsson, 2015; Straume & Bertelsen, 2015). Then, we discuss how other types of travel-behaviour such as change of destination, departure-delay or trip-cancellation, may be included in the model.

The increase in generalized transport costs for road users caused by a road disruption includes all the extra travel costs the road users are exposed to due to the disruption. In line with the general economic behaviour of minimizing the use of resources, the basic principle is that road users choose the alternative providing the lowest generalized travel costs. Generalized travel costs comprise both pecuniary costs and time costs, and they indicate the total use of resources for the individual upon completing a trip (see, for example, Button (2010)). In contrast to Jenelius and Mattsson (2015), assuming that the time cost per hour is equal for all groups of vehicles, our model takes into account the variation in valuation of time between different road users. Still, we assume people's valuation of time within a specific group of travellers to be independent of whether they wait or take the detour option. The time value for each vehicle is further elaborated by $k_j = k_{0j} \cdot vo_j$, where k_{0j} is the value of time for road-user group j when the traffic flow is normal, and parameter vo_j is average vehicle occupancy. The latter will be most relevant for vehicles such as private cars and buses and not relevant for freight vehicles where vo_j equals one. The use of heterogeneous valuation of time ensures that time for freight vehicles or busses can be valued higher than, for example, time for leisure travellers in private cars.

The parameter Δt is the difference in travel time between the alternative route and the original route, $\Delta t > 0$. The increase in time costs of taking a detour is thus $k_j \cdot \Delta t$. In addition, our model includes the change in pecuniary cost, Δp_j, associated with choosing the detour. Pecuniary costs of taking the detour were addressed by both Bråthen et al. (2008) and Straume and Bertelsen (2015) in the case of landslides, and they argued that one should include extra pecuniary costs. Since the pecuniary costs may vary between vehicles groups (for instance are the ferry tickets, tolls and vehicle operating costs for heavy vehicles higher compared to private motor vehicles) these costs also hold the subscript j. It follows that the total increase in generalized transport costs, G, for a vehicle taking the detour is $\Delta t \cdot k_j + \Delta p_j$.

2.4 Basic Model - Wait or Detour

Jenelius and Mattson (2015) assume that road users decide whether to wait for the road to open or to take the detour based purely on the difference in travel time between the two options. However, as argued in section 2.2, travellers consider generalized travel costs. This is reflected by extending the model to comprise k_j and Δp_j Hence, if $(\Delta t \cdot k_j + \Delta p_j) \geq q \cdot k_j$, all road users in group j will choose to wait and not take a detour. The annual expected economic loss experienced by the road users satisfying this criterion at a specific section of road is denoted R_w and is presented in equation (2).

$$R_w = \sum_{i=1}^{n} \sum_{j=1}^{m} \sum_{s=1}^{z} H_{is} \cdot X_{js} \cdot G_{ijs} = \sum_{i=1}^{n} \sum_{j=1}^{m} \sum_{s=1}^{z} H_{is} \cdot \frac{x_{js} q_{is}^2}{2} \cdot k_j \qquad (2)$$

In (2), H_{is} is the disruption frequency for the type of incident i, where $i = 1, 2, \dots, n$, in season s, where $s = 1, 2, \dots, z$, causing closure of a specific section of road (accident, closed mountain pass etc.). Subscript j, where $j = 1, 2 \dots, m$, indicates a type of road user or vehicle group affected (passenger vehicles, trucks, busses, etc.). It is useful to include the seasonal dimension, since some incidents are more prominent during winter than summer (for example, preventively closed roads during winter storms), and traffic volume, x, may vary significantly throughout the year. It follows from the assumption of constant traffic flow during the disruption that road users, on average, wait half the duration of the disruption (Jenelius & Mattsson, 2015).

When $(\Delta t \cdot k_j + \Delta p_j) < q \cdot k_j$, a situation arises where some road users in group j wait and some take the detour. Specifically, only the road users departing when the remaining duration of the disruption is equal to or less than t_w will wait for the road to open instead of taking the detour. t_w equals the remaining duration of the disruption at the point of time when the economic loss is equal between taking the detour and waiting for the road to open. The expected economic loss (G) for a road user departing at this point in time is $\Delta t \cdot k_j + \Delta p_j$.

Let R_d be the total economic loss for those who wait and those who take the detour when $(\Delta t \cdot k_j + \Delta p_j) < q \cdot k_j$, as expressed in (3). See detailed workings and illustration in Appendix.

$$R_d = \sum_{i=1}^{n} \sum_{j=1}^{m} \sum_{s=1}^{z} H_{is} \cdot X_{js} \cdot G_{ijs}$$

$$= \sum_{i=1}^{n} \sum_{j=1}^{m} \sum_{s=1}^{z} H_{is} \cdot x_{js} \cdot [-\frac{1}{2k_j} (k_j \Delta t + \Delta p_j)(k_j \Delta t + \Delta p_j - 2k_j q_{is})] \qquad (3)$$

Hence, (3) provides total economic loss for all types of disruptions (i) in different seasons (s) for all vehicle groups (j). It is evident that R_d increases with increased frequency of disruptions, increased amount of traffic affected, the increase in monetary costs and travel time, and the increase in the value of time and road-closure duration. The total annual expected economic loss for road users due to defined types of disruptions on a specific section of road is $R = R_d + R_w$.

Our model extends Jenelius and Mattson's (2015) model by considering increase in generalized transport costs, and thereby allowing for road users to have different values of time and increased pecuniary costs of taking a detour, instead of only estimating time loss due to disruption. Straume and Bertelsen (2015) and Bråthen et al. (2008) consider in their models the generalized costs related to choosing the detour alternative. However, these models do not include the situations where some road users choose to wait for reopening of the road while others choose to take the detour depending on their generalized transport costs at the time of arrival at the road closure. For incidents like avalanches and landslides, this may not be relevant since these road closures are typically of long duration and possibly leading to other behavioural characteristics. However, when extending the model to include the economic loss due to shorter road closures, this is highly relevant.

2.5 Extensions of the Model

2.5.1 Alternative Behaviour of Road Users

It is rather strict to assume that travellers either wait or take the detour in response to a disruption. However, some of the alternative behaviours mentioned above may easily be included in the proposed model. What is needed is more-detailed data on traffic demand, available transport modes and destinations. If alternative transport modes exist, such as railway, Δp_j equal the difference in pecuniary costs for road user j between driving the original road route and the railway ticket, and Δt equal the difference in time use between taking the original route and going by train. It is also possible to adjust for differences in time cost per hour between the two modes. If detailed data are not available, it is also possible to make assumptions, as shown in Hallenbeck et al. (2014), or apply transport models (such as NTM6 (Bertelsen et al., 2015)) to obtain proxies of these data.

Hallenbeck et al. (2014) assume that the traveller will choose to either abandon the trip, divert to another destination, or delay departure if these options are less costly than taking the detour or waiting at the location for the disruption. Further, they make assumptions on how much the alternative behaviours are valued in relation to the known valuation of waiting or taking a detour. What kinds of travel behaviours are relevant to include will depend on several factors, such as the duration of the disruption, the availability and cost of alternative transport modes and the characteristics of routes and destinations. As Hallenbeck et al. (2014) noted, for example, no trucks detoured during the two-day closure due to flooding that occurred on I-5 in Washington in 2009. A recent study from the Saltfjellet mountain area, which is the empirical context of this paper, supports this observation (Bardal, 2017). Bardal (2017) shows that total number of vehicles using this road section, is to a limited extent affected by traffic flow disruptions, probably because of the long and costly detour routes. In addition, preventive road closures due to adverse weather and road closures associated with accidents in rural areas normally last only a few hours and rarely exceeds 24 hours. This most likely excludes options such as changing to alternative transport modes, because these modes are few and the frequency of scheduled public transport is limited.

2.5.2 Value of Time When Delayed

The proposed model in section 2.4 assumes a constant value of time (k). However, studies have revealed that road users put higher value on time when delayed (see, for example, Carrion & Levinson (2012) for a review of research on valuation of travel time reliability). Increasing the value of k_j in equations (2) and (3) will increase the expected economic loss due to the disruption. If k_j increases, $\Delta t \cdot k_j + \Delta p_j$ increases. Consequently, we arrive at the indifference point $t_w \cdot k_j = \Delta t \cdot k_j + \Delta p_j$. Rearranging the expression to $t_w = \Delta t + \frac{\Delta p_j}{k_j}$ makes it easy to see that when k_j increases, the relative importance of Δp_j decreases. The departure time where the road user is indifferent between waiting for the road to reopen or take the detour move closer to the reopening time of the road, which means that the indifference-point of time t_w is reduced. This will make the detour the preferable alternative for briefer closures (lower q), and a larger proportion of travellers will find it beneficial to take the detour.

Although the literature on valuation of travel time reliability is large, the value of reliability estimates exhibits a significant variation across studies partly due to variation in the procedure for quantifying travel time reliability and regional differences (Carrion & Levinson, 2012). In a Norwegian study, Østli et al. (2015) estimated the value of time for passenger transport in severely congested traffic to be 3.0 times higher than the value of time in uncongested traffic for trips longer than 70 kilometres. In a related study, Halse et al. (2010) found in a stated preference study of freight transport that shippers with hired transport, shippers with their own freight accounts and carriers valued time 5.6 times higher on average during delays than when traffic ran smoothly.

The higher time valuations suggested by Halse et al. (2010) and Østli et al. (2015) relate to congested traffic in line with the urban focus of most previous research on travel time reliability (Carrion & Levinson, 2012). The values suggested by Halse et al. (2010) and Østli et al. (2015) could be transferable to the situation of waiting for the road to open after a disruption. However, the corresponding value of time for those who take the detour is uncertain. It is reasonable to believe that the value of time is lower for those who take the detour compared to standing in line waiting for the road to open. However, they still experience delays and possible loss of goodwill for freight transport that is unable to meet its obligations. More research is required to be able to conclude on how road users value time under various conditions (for example, time of the year, time of day, and various trip purpose) when they experience unexpected delays.

2.5.3 Considering Road Users' Risk Aversion

The model presented in section 2.4 assumes risk-neutral road users. However, it is more reasonable to believe that the road users are risk averse (Lo, Luo, & Siu, 2006). Hence, when choosing between the two options of waiting for the road to reopen or taking the detour, they will not only consider the expected economic costs of the two alternatives but will also consider the uncertainty associated with these costs. If the estimated costs are equal between the two alternatives, a risk-averse road user will choose the alternative with the lowest associated uncertainty.

Modelling risk aversion requires some assumptions on travellers' utility functions. The quadratic utility function is often used in the literature, including the transportation literature, to understand risk behaviour (Carrion & Levinson, 2012; Keeney & Raiffa, 1976). This function possesses the property of risk aversion and deriving the expected utility of a choice with uncertain consequences relying solely on the vehicle's mean economic loss ($\bar{G}$) and the corresponding variance (σ^2). In our case, comparing the average expected costs for each vehicle of waiting for the road to reopen ($\overline{G_w}$) or taking the detour ($\overline{G_d}$) and the expected costs including uncertainty for each alternative denoted G_w^* and G_d^*, can be expressed as:

$$G_w^* = \overline{G_w} + c \cdot \sigma_w^2 \tag{4}$$

$$G_d^* = \overline{G_d} + c \cdot \sigma_d^2 \tag{5}$$

where σ_w^2 and σ_d^2 are the variances in economic loss of waiting and taking the detour, respectively. When $c = 0$, the road user is risk neutral, which is the assumption built into the model in section 2.4. The more risk averse the road user is, the higher the value of c. The road user will choose to wait for the road to reopen if $G_w^* < G_d^* \Leftrightarrow \overline{G_w} + c \cdot \sigma_w^2 < \overline{G_d} + c \cdot \sigma_d^2$. It follows that the road user will wait if:

$$\overline{G_d} - \overline{G_w} > c \cdot [\sigma_w^2 - \sigma_d^2] \tag{6}$$

If we assume that the uncertainty of waiting time due to a disruption is greater than that of the available detour options, $\sigma_w^2 > \sigma_d^2$. Hence, the more risk averse a road user is (the higher c), the larger $(\overline{G_d} - \overline{G_w})$ must be if the road user should want to wait. Consequently, a greater value of c and a larger difference in variance imply that a larger proportion of travellers will choose the detour.

3.0 Case and Data Description

To illustrate the application of the model, we introduce an example. Two types of traffic flow disruptions are studied at a specific road section. The case and data are described in sections 3.1 and 3.2, respectively.

3.1 The Case: European Highway 6 from Mo i Rana to Storjord

The road section studied is the European Highway 6 (Ev6) between Mo i Rana and Storjord in the county of Nordland, Norway. This part of Ev6 connects the northern and southern parts of Norway and goes through rural areas over one mountain pass (see Figure 1). The region is located at the Arctic Circle, and the climate can be rough, particularly in winter. The mountain pass has a polar climate, according to the Köppen Geiger classification (Böcker, Dijst, & Prillwitz, 2013).

Figure 1 Map showing the studied road between Mo i Rana and Storjord with detour routes along the coast and through Sweden (source: Google Maps).

3.2 Data Description

This study considers two different kinds of road closures that frequently hinder traffic flow on the studied road section. First, the 20-kilometres stretch of road on top of the mountain pass (named Saltfjellet in Figure 1) is closed preventively or traffic is led in a convoy when the weather is too harsh for free movement of vehicles. When traffic is led in convoy, the vehicles have to wait for and follow a leading vehicle across the mountain pass and the speed is restricted to 40 kilometres per hour (NPRA, 2012). According to the Norwegian Public Road Administration’s guidelines (NPRA, 2012), weather conditions that call for closure of the road are one or a combination of the following situations: restricted visibility, narrow or impassable road caused by snowdrift, or risk that vehicles will be blown off the road by strong winds. Second, the road is often closed for a period due to traffic accidents. The road section is a two-lane road, and sometimes the road is completely closed, while in other cases, one lane is kept open during clean-up after the accident. The dataset comprises information on preventive road closures and convoys due to adverse weather on the mountain pass and road closures due to accidents on the road section between Mo i Rana and Storjord during the period 2010-2014.

Table 1 summarizes statistics of the road closures. Each period with a convoy was treated as a road closure with a maximum duration of two hours. This is because the convoys are run continuously, and the maximum waiting time for a road user between each convoy will be approximately two hours. Of the total body of messages reporting accident-related road closures, approximately 75 per cent concerned total road closure. In the remaining 25 per cent, one lane was still open, and these observations were omitted from the analysis. Moreover, there was some unsystematic missing information with respect to duration of the closures. The missing data were interpolated from the complete registrations.

Table 1: Statistics on road closures at Ev6 between Mo i Rana and Storjord 2010-2014 (Source: The Norwegian Public Road Administration)

	Winter	*Summer*	*Year*
Average annual number of preventive road closures [a]	45.8	1.80	47.6
Average duration of each preventive road closure (hours)	3.61	1.73	3.54
Median duration of preventive road closures (hours)	2.00	1.28	2.00
Average annual number of periods of total closures due to accidents	11.9	3.5	15.4
Average duration of each total closure due to accidents (hours)	1.29	0.94	1.19
Median duration of total road closures due to accidents (hours)	0.73	1.00	0.81

[a] Figures include periods with convoys during the closure. The average frequency between convoys was assumed to be two hours. Hence, the waiting time for the road users was a maximum of 2 hours during periods with a convoy.

The preventive and accident-caused road closures at the studied road section share some common characteristics. They are both unexpected to a certain degree, although the risk of both preventive road closures and accidents increase in adverse weather (Bardal & Mathisen, 2015; Thomas H. Maze, Agarwal, & Burchett, 2006). They both happen frequently during winter and less during summer, which demonstrates the importance of considering the seasonal aspect in equations (4) and (5). Winter months are defined as October to April, while the remaining 5 months are defined as summer. In the northern parts of Norway, vehicles are allowed to be equipped with winter tires with spikes from October 16 to May 1 (Lovdata, 2014). The durations of the road closures are all within the interval 0-24 hours, with an annual average of 3.54 and 1.19 hours for preventive and accident-caused road closures, respectively. The median durations of road closures show that the distributions are skewed to the left in all time-periods except for accident-related road closures in summer. This means that most of the road closures are of short duration.

The Norwegian Public Road Administration (NPRA) has provided data on traffic volume measured by the number of vehicles passing an electronic counter (inductive loops in the asphalt covering (NPRA, 2011b)). In accordance with NPRA's definition (NPRA, 2011b), heavy vehicles are defined as vehicles ≥ 5.6 meters and are assumed to represent freight transport. Vehicles < 5.6 meters are assumed to represent passenger transport. This definition holds well in winter when most of the road closures take place, because at this time of year, there are no regular bus routes and there are few caravan-driving tourists. However, in summer, there are some tourist buses and caravans, which will also be included in the number of heavy vehicles. Since this is a rural area with virtually no settlements, most of the trips on the road section are long-distance (trips exceeding 100 km in accordance with NPRA (2013)).

In our example, vehicles are divided into two broad groups – private motor vehicles and heavy vehicles – where heavy vehicles represent freight transport and private motor vehicles mostly represent tourist, leisure trips or long-distance business trips. Although the valuation of time for business trips are normally higher than for leisure trips, it has not been possible to separate these trips in the analysis. A weighted value of time for private motor vehicles in accordance with NPRA's guidelines (2014) has therefore been used in the analysis. However, the model allows for other types of grouping of the vehicles with corresponding values of time. Each incident has been treated separately in the model, with monthly average values for passenger and heavy vehicle traffic flow (x) and an average vehicle occupancy (vo) of 2.0 and

1.0 for passenger and heavy vehicles, respectively (NPRA, 2014). These assumptions, in combination with the recommendation of NPRA (2014), produced time values per private and heavy vehicles of 50 Euro and 72 Euro, respectively.

The average daily traffic (ADT) varies significantly throughout the year. The ADT for the years 2010-2014 is listed in Table 2. The ADT is, on average, 175 per cent and 113 per cent higher in summer than in winter for passenger vehicles and heavy vehicles, respectively. The statistics shows that the proportion of heavy vehicles was 23 per cent higher in winter than summer, which is a conservative indicator of seasonal deviation in freight transport considering the increased presence of tourist busses and caravans during summer.

Table 2: Average daily traffic in the period 2010-2014 on Ev6 between Mo i Rana and Storjord (source: NPRA).

Season	*Total*	*Private cars*	*Heavy vehicles*	*Share Heavy Vehicles*
Winter	555	380	175	32%
Summer	1 417	1 044	373	26%
Average	914	657	258	28%

The two alternate detour routes to the studied road are the eastern route going through Sweden and the western route along the coast, both of which are associated with a considerably longer transport distance and higher time use (see Figure 1). The two detour options represent different characteristics. While the coastal route is shorter in distance, it has a considerably lower average speed and relatively high pecuniary costs due to two ferry connections. There are no ferries on the Sweden route. However, the route passes two mountain areas exposed to adverse weather. In case of adverse weather conditions in the larger region, both the coastal route with two ferries and the Sweden route with two mountain passes may experience weather conditions leading to road closure at the same time as the road stretch across Saltfjellet. In Table 3, the two routes with corresponding distances are listed and compared with the original road section. All three alternatives are connected at Mo i Rana in the south and at Storjord in the north.

The first ferry on the western route (Forøy – Ågskardet) takes 10 minutes, with 20 departures each day. The ferry tickets depend on vehicle size and transport length (Jørgensen et al., 2004). At this specific ferry crossing, the ticket prices range from 7.92 Euro to 75.49 Euro (2016 prices, 1 Euro = 9.22 NOK) for one vehicle with driver (Torghatten Nord, 2016). The second ferry on this route (Jektvik – Kilboghamn) takes 1 hour with 5 daily departures in winter and 11 daily departures in peak season (mid-summer). The price for one vehicle with driver ranges from 20.72 to 133.73 Euro (Torghatten Nord, 2016). The distance dependent vehicle costs will vary between the routes because of the large difference in travel distance. There are no tolls on either of the road sections.

Table 3: Alternative routes for road transport at Ev6 from Mo i Rana to Storjord (source: Google Maps).

Route: Mo i Rana – Storjord	*Distance (kilometres)*	*Estimated time without queue (hours)*
Original route: Ev6 (mountain pass)	110	1.33
Alternative 1: East on Ev12 through Sweden on Ev45 and 95 (border crossing)	625	7.08
Alternative 2: West on Rv12 along the coast on Fv17 (including 2 ferries)	382	7.01

4.0 Results and Discussion

4.1 Expected Economic Loss due to Preventive and Accident-related Road Closures

By inserting parameter values from the case presented in Section 3 into equations (2) and (3), we are able to estimate the risk ($R = R_w + R_d$) associated with preventive and accident-related road closures. The results are listed in Table 4.

The expected economic loss (R) associated with accident-related and preventive road closures is clearly highest in the winter and for preventive road closures. The statistics on the number and duration of road closures in Table 1 also indicate this result. If measures were implemented to completely remove the disruptions, the drivers using this road section would experience average annual benefits of 630 300 Euro due to travel time savings and savings in pecuniary cost related to avoiding waiting for the road to open or taking expensive detours. About 98 per cent of the benefits relate to the winter season. Summarizing time costs and pecuniary costs for road users driving the 110 kilometres between Mo i Rana and Storjord each winter without disruptions are, on average, 15.2 million Euro. It follows that the measured costs related to disruptions amount to approximately 4 per cent of this amount. According to the Norwegian cost-benefit analysis framework, the present value of benefits from removing these disruption-costs would amount to approximately 12.5 million Euro (cost and benefits are discounted 40 years with a discount rate of 4 per cent (NPRA, 2014)). In addition, other types of benefits not measured in this paper would arise with removing the disruptions. Examples of other benefits are those related to increase in travel-time reliability and travel-time savings due to increase in driving speed if the road improvements (for example, a tunnel through a difficult mountainous area) makes the driving conditions better in general.

An improvement in road standards would reduce generalized travel costs and generate new traffic. Since the benefits stated above only include existing traffic, the estimate must be considered conservative. Examples of projects reducing the risk in this context are building a tunnel through the mountain or road superstructures at particularly exposed areas, improvements to the road structure, increased levels of winter maintenance (ploughing and gritting), and reduced response times for emergency services when accidents occur. The estimated benefits in this paper would only to a limited degree contribute to the profitability of a large-scale investment such as a tunnel but could cover all the costs for a less costly measure such as improved maintenance. In addition, added up with all the benefits of reduced winter problems (including the value of increased travel time reliability, increased driving speed, less need for spike tires etc.), the contribution to the profitability of a larger infrastructure project could be considerable, as shown in the tunnel project studied by Hagen and Engebretsen (1999) where the benefit-cost ratio increased from 0.42 to 0.9.

Table 4: Estimates of road users' annual expected economic loss related to preventive and accident-related road closures on the Ev6 road section between Mo i Rana and Storjord in the period 2010 to 2014.

	R preventive road closures (Euro)	*R accidents (Euro)*	*R Total (Euro)*
Average per winter	593 700	21 400	615 100
Average per summer	7 600	7 600	15 200
Average per year	601 300	29 000	630 300

In Figure 2, the cumulative distribution of expected economic loss for individual incidents is shown for both vehicle groups. Approximately 75 per cent of the incidents were associated with an expected economic loss less than 3 000 Euro and 4000 Euro for heavy vehicles and passenger vehicles, respectively. Evidently, it would be most important for the road authorities to implement measures preventing the amount of shorter disruptions. This could imply both less costly measures such as increasing the operational level (more snow ploughing and gritting capacity) and more expensive investments to improve the quality of road stretches frequently subject to road closures.

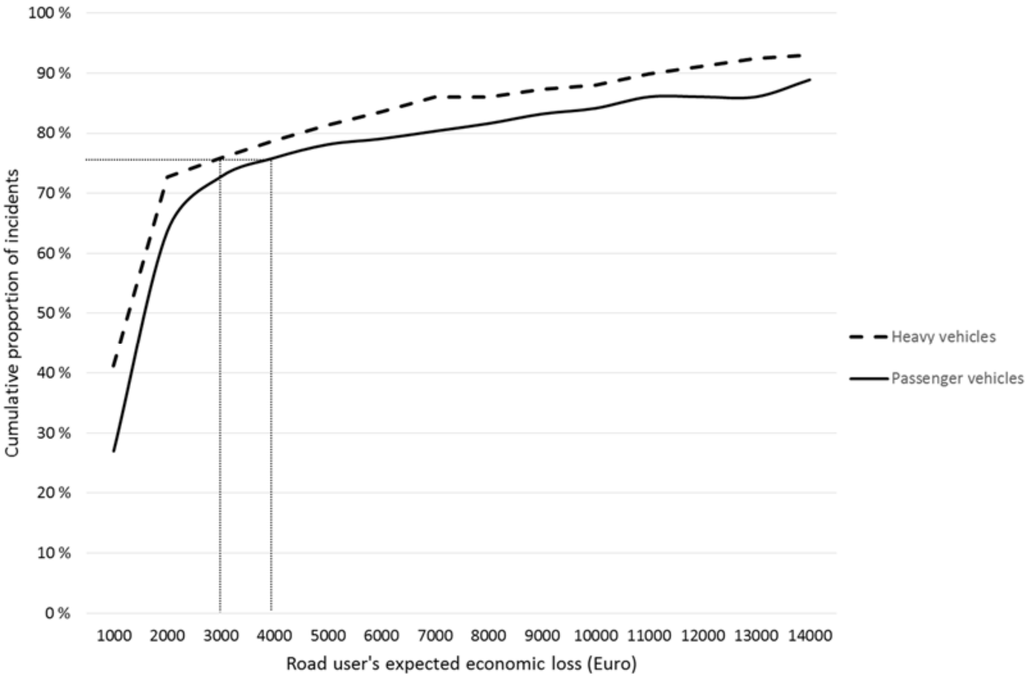

Figure 2: Cumulative distribution of road users' expected economic loss related to road closures on the Ev6 road section between Mo i Rana and Storjord.

The detour costs were slightly lower for the route through Sweden, so this route was chosen as an alternative to Ev6 between Mo i Rana and Storjord. If the Swedish detour option had been unavailable, the travellers would have chosen the coastal route with virtually the same outcomes.

In Figure 3, the cumulative distribution of the durations of the road closures on the studied section of road is presented. For a detour to be a relevant alternative, the duration of the road closure had to be at least 7.8 hours and 10.2 hours for passenger and heavy vehicles, respectively, as shown in Figure 3. This was never the case with accident-related road closures, but it was the case of preventive road closures in 5.4 per cent of the incidents for passenger vehicles and 3.5 per cent of the incidents for heavy vehicles.

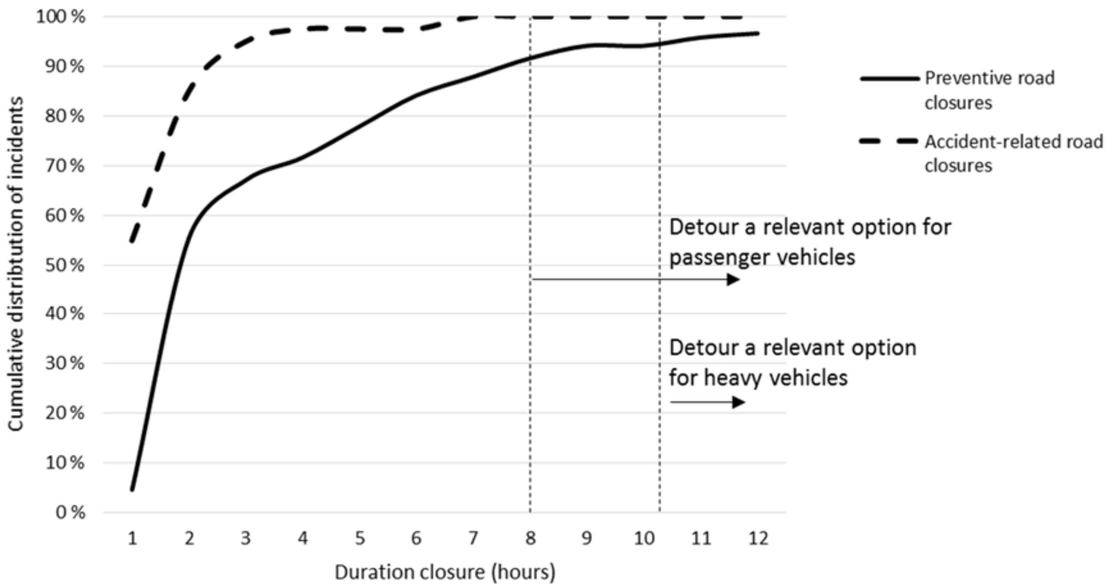

Figure 3: Cumulative distribution of duration of the preventive and accident-related road closures on the Ev6 road section from Mo i Rana to Storjord.

4.2 Sensitivity to the Assumptions

4.2.1 Congestion

In this study, the Δp and Δt values are high because of the rural context with few alternative roads. This may be opposite in urban areas with more alternative routes available, although in urban areas, congestion on the detour route may be a problem. Congestion on the detour will increase Δt and, hence, increase the costs of taking the detour. A larger portion of the road users will then choose to wait for the road to reopen and not take the detour. Congestion on the detour route may also be a problem in rural areas, particularly if scheduled services with limited capacity interrupt the route, which is the case for ferries at the coastal route in this study. If the capacity of the ferries is too low to handle the increased traffic, the vehicles will be delayed in the queue and Δt will increase. This implies that the estimated time for the coastal route in Table 3 must be considered conservative. However, this does not affect the results in this study, since the eastern route through Sweden had the lowest generalized transport costs of the two alternatives and was used in the analysis.

4.2.2 The Value of Time (k)

The valuation of time (k) is a question for debate, as discussed in section 2.5.2. Since the duration of the road closures in our case was relatively low and the alternative detour costs high, taking the detour was relevant for road users on only a few occasions. If the higher values of time suggested by Halse et al. (2010) and Østli et al. (2015) are used, taking the detour was a relevant option in 11.5 per cent of the incidents for both passenger and heavy vehicles. Correspondingly, the annual expected economic loss due to the disruptions on the studied section of road would equal the amounts listed in Table 5. With these higher time values, the disruptions cause a 15.2 per cent increase in expected costs for drivers on this section of road in winter compared to the situation with no disruptions.

Table 5: Annual estimates of road users' expected economic loss related to road closures on Ev6 Mo i Rana – Storjord in the period 2010 to 2014 using a time value adjusted for lateness.

	R preventive road closures (Euro)	*R accidents (Euro)*	*R Total (Euro)*
Average per winter	2 226 200	87 700	2 313 900
Average per summer	29 800	29 600	59 500
Average per year	2 256 000	117 300	2 373 400

The estimated economic loss is also sensitive to traffic volume. The more road users, the higher the total expected economic loss. Traffic flow is assumed constant; however, it is well known that it may vary among the hours of the day, the days of the week and from season to season. In our example, we have used monthly averaged values of traffic volume, but with the availability of electronic counters continuously measuring traffic flow, the traffic volumes could easily be more detailed. We recommend that the specific context determine the necessary level of detail on traffic volume. The present value of benefits in Table 5 amounts to 47 million Euro. Comparison shows that by using the higher time values (see Table 5), the economic loss is nearly 4 times higher than when time values not adjusted for lateness are used (see Table 4). This example emphasizes the importance of time valuation when assessing the economic loss of disruptions.

4.2.3 Risk Averse Behaviour

The expected economic losses estimated in Table 4 and Table 5 assume risk-neutral road users. However, if the variances in expected economic loss of the two alternatives of taking the detour or waiting for the road to reopen and the road user's utility function are known, risk behaviour can be included in the model, as discussed in section 2.5.3.

Following the example in section 2.5.3, assuming a quadratic utility function, a sensitivity test has been conducted showing how varying degrees of risk-averse behaviour impact the road user's decision of whether to take the detour or wait for the road to reopen. As shown in equation (6), the road user will choose to wait if $\overline{G_d} - \overline{G_w} > c \cdot [\sigma_w^2 - \sigma_d^2]$. From our example, we know the values of $\overline{G_d}$, $\overline{G_w}$ and σ_w^2 for passenger and heavy vehicles (see Table 6), while σ_d^2 and c are unknown. If we assume that the variance in the expected economic loss related to taking the detour (σ_d^2) is zero, inserting the numbers in Table 6 into equation (6) yields that passenger vehicle drivers will only consider waiting for the road to reopen if their risk constant c is less than 0.46. Similarly, heavy vehicle drivers will only consider waiting for the road to open if their risk constant c is less than 0.70.

Table 6: Parameter values for assessing risk aversion on the road section between Mo i Rana and Storjord.

	$\overline{G_d} = \overline{\Delta t} \cdot k_j + \overline{\Delta p}$ *(Euro)*	$\overline{G_w} = \bar{q} \cdot k_j$ *(Euro)*	σ_w^2 *(Euro)*
Passenger vehicles	394	162	503
Heavy vehicles	732	230	714

Consequently, including risk aversion in the model affects road user's choice of whether to wait for the road to reopen or take the detour. When assuming risk-neutral road users with full information about the duration of the closure, in most of the observations, they would choose to wait and not take the detour. However, when risk aversion is included, the conclusion may be opposite, depending on the magnitude of the road user's risk aversion and the difference in variance in the expected economic loss of the two alternatives.

In our example, we have assumed that the variance in the expected economic loss by taking the detour is zero. This is hardly the case with the two alternative routes relevant for our example. There are reasons to believe that the variance in travel time and, thus, the expected economic loss by taking either the coastal route, which includes two ferry trips, or the Sweden route, which includes two mountain passes, are significant. If they are as high as the variance in expected economic loss by waiting for the road to reopen, we are back to the same situation as when assuming risk-neutral behaviour, since $(\sigma_w^2 - \sigma_d^2)$ would then equal zero and the decision would depend on the difference between $\overline{G_d}$ and $\overline{G_w}$ (see equation (6)).

4.2.4 Full Information

A final assumption in the model that should be mentioned is that road users have full information about how long the road will be closed and detour options. This is a strict assumption; however, with the available technology and Intelligent Transport Systems (ITS) at least the second assumption is valid or should be able to achieve in the future. Uncertainty is unfortunately an inherent property of weather-related incidents, so although indications on driving conditions are to some extent available by forecasts and announcements from police and authorities, some uncertainty will still remain. It is relevant to consider projects that will increase road users' access to information if this can reduce their economic loss related to road closures.

5.0 Conclusions and Implications

There are different types of incidents that frequently cause temporary traffic flow disruptions. This study has focused on road users' expected economic loss related to incidents causing road closures. The aim of the study has been twofold. First, a model has been developed to assess the expected economic loss related to unexpected road closures with the purpose of including the benefit of reducing this loss in cost-benefit analyses when relevant. A few models have addressed this question with a focus on landslides, but to our knowledge, this is the first attempt to make a generic framework for all types of single link failures in rural areas. Second, for illustration purpose, the model has been applied on two different types of incidents—preventive and accident-related road closures—on a section of Ev6 located at the Arctic Circle in the northern part of Norway.

The studied area is rural and characterized by a harsh climate, mountainous topography and few detour alternatives. The decision on whether to make improvements in infrastructure to reduce the frequency and length of road closures in this type of area, will be based on better information by completing the analysis conducted in this study. Including the benefit of completely removing this economic burden on existing road users in a cost-benefit analysis of a relevant project would increase the present value of benefits of the project by 12.5 million Euro. It is important to emphasize that this benefit only covers the travel-time savings related to avoiding waiting for the road to open or taking detours. In addition, comes other types of benefits not measured in this paper such as benefits related to increase in travel-time reliability and travel-time savings due to increase in driving speed if the road improvements (for example, a tunnel through a difficult mountainous area) makes the driving conditions better in general. There is some evidence in the literature that time costs should be higher in the case of unexpected delays due to missed appointments, late delivery of goods and lost goodwill. Correspondingly, the present value of a project removing the unexpected traffic flow disruptions would then increase to 47 million Euro.

Another policy problem related to the traffic flow disruptions studied in this paper is that the costs of the disruptions fall on the same communities over and again. This may on one side have reputational disbenefits for an area and be damaging to inward investments, and on the other side effect product prices and rental costs. This is a distributional matter which the CBA does not handle. However, according to the assessment guidelines for Norwegian road projects (NPRA, 2014), for example, distributional effects such as this are to be considered before recommendations are made. This is one reason why the results of CBAs should be used with care.

We argue that the expected economic loss associated with temporary traffic flow disruptions should be incorporated in road project assessment tools and that this will improve the decision process. We argue that this would enhance the probability that appropriate decisions are made regarding the development and improvement of transportation facilities. The model developed should easily fit within the existing cost-benefit framework and thereby improve its quality by including unexpected delay costs as monetary values. Moreover, the flexibility of the model allows application to all kinds of disruptions causing road closure. Two types of incidents not studied here, but having correctly received much attention, are landslides and avalanches. These incidents often cause road closures of long duration. Considering the expected climate change and, with it, more days with strong winds and precipitation in the studied region, the frequency of these incidents are likely to increase in the future, thereby increasing the associated risk for the road users.

As discussed in section 4, it has been necessary to make assumptions about some of the parameters in the model. Depending on the context, the estimates from the model may be sensitive to these assumptions to a varying degree. Still, our assumptions extend previous models, and examples are given regarding how to extend the model by, for example, including risk behaviour and higher time values when road users are delayed. Another limitation is the quality of the data on road closures. Approximately half of the registrations of closures related to accidents were lacking sufficient information to conclude unambiguously about the duration of the closure. In addition, considering the well-known problem of underreporting of accidents, there are reasons to believe that traffic flow has been disrupted more frequently than the dataset indicates. Consequently, there is a need for improved registration of data related to road closures. Despite the limitations of the dataset, it shows the applicability of the model on a specific road section.

Admittedly, other benefits exist that are not considered by this model. For example, the studied road section also represents a detour option for the coastal route and the Sweden route. Neither the benefit of improving the detour function for other routes nor the benefit for new generated traffic are included in this estimate. On the other hand, one should be aware of the on-going discussion of double counting of benefits.

Available data did not reveal how many vehicles actually diverted during the disruptions. Future research including analyses using data on this type of behaviour, would be a valuable contribution to the literature. In addition, in this study the model has only been applied to two types of disruptions. A suggestion for further research is to apply the model to other types of incidents, such as landslides and avalanches, in addition to other contexts, which could lead to other types of road-user behaviour.

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Appendix

One type of disruption (closed road) lasting q hours is analysed.

H represents hazard and is defined as the number of disruptions per year at a specific road section.

R is the total risk due to a disruption in the transport system. Total risk is in this study is defined as the expected economic loss experienced by the road users when an incident causes the road to close.

$x =$ Traffic flow (number of vehicles per hour)

$X = x \cdot q =$ Number of vehicles affected by the disruption

$G =$ Increase in generalized transport costs due to a disruption ($G > 0$).

$R = H \cdot X \cdot G$

$\Delta t =$ Difference in travel time between the alternative and the original shortest route ($\Delta t > 0$).

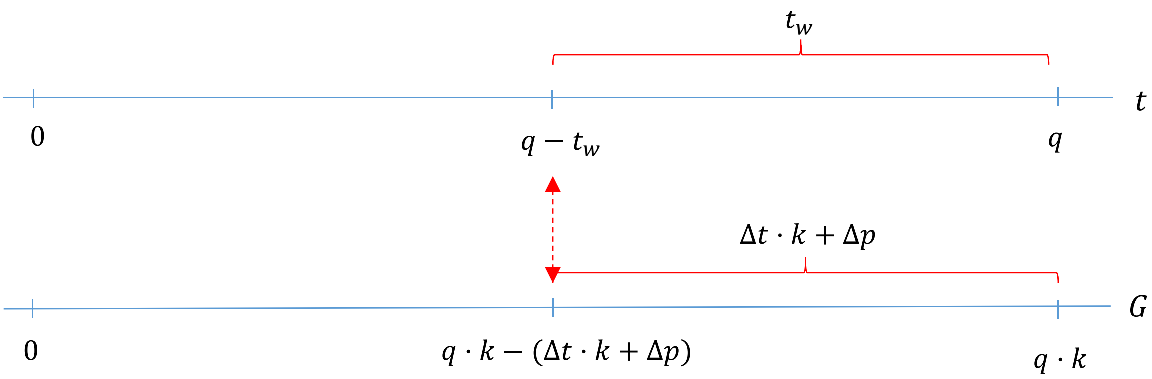
$k =$ Value of time (per hour) (assumed constant)

$\Delta p =$ Difference in pecuniary costs between the alternative and the original shortest route ($\Delta p > 0$).

$G_d = \Delta t \cdot k + \Delta p =$ Increase in generalized transport costs of taking the detour

$t_w =$ The maximum time the road users are willing to wait instead of taking the detour
when $(\Delta t \cdot k + \Delta p) < q \cdot k$.

We assume that the road users choose an alternative in order to minimize their generalized transport costs.



Situation 1:

If $(\Delta t \cdot k + \Delta p) \geq q \cdot k$ for the road users, they will choose to wait and not take the detour.

Assuming that x is constant and that the road users, on average, wait half the time of the closure, the total increase in generalized costs per year for the road users satisfying this criterion are denoted R_w:

$$R_w = H \cdot X \cdot G = H \cdot x \cdot q \cdot \frac{q}{2} \cdot k = H \cdot \frac{xq^2}{2} \cdot k \tag{A.1}$$

Situation 2:

If $(\Delta t \cdot k + \Delta p) < q \cdot k$ for road users, only those who wish to depart after $q - t_w$ will wait for the road to reopen. The others will want to take the detour.

A) Road users who wait for the road to reopen:

Equivalent to equation (A.1), for those who want to wait

$$(X \cdot G)_A = x \cdot t_w \cdot \frac{t_w}{2} \cdot k \tag{A.2}$$

At time $q - t_w$ after the road is closed, the generalized transport costs of waiting are equal to the generalized transport costs of taking the detour: $t_w \cdot k = \Delta t \cdot k + \Delta p$. This can be rearranged to $t_w = \frac{\Delta t \cdot k + \Delta p}{k} = \Delta t + \frac{\Delta p}{k}$

Substituting this for t_w in equation (A.2) gives:

$$(X \cdot G)_A = x \cdot \left(\Delta t + \frac{\Delta p}{k}\right) \cdot \frac{\left(\Delta t + \frac{\Delta p}{k}\right)}{2} \cdot k = x \cdot \frac{k}{2} \cdot \left(\Delta t + \frac{\Delta p}{k}\right)^2 \tag{A.3}$$

B) Road users who take the detour:

Those who wish to depart earlier than $q - t_w$ take the detour because the cost of taking it is less than the cost of waiting.

Number of vehicles taking the detour:

$$x \cdot (q - t_w) = x \cdot \left(q - q \cdot \left(\frac{\Delta t \cdot k + \Delta p}{q \cdot k}\right)\right) = x \cdot \left(q - \left(\frac{\Delta t \cdot k + \Delta p}{k}\right)\right)$$

$$= x \cdot \left(\frac{q \cdot k - \Delta t \cdot k - \Delta p}{k}\right) = x \cdot (q - \Delta t - \frac{\Delta p}{k})$$

The total increase in generalized transport costs $(X \cdot G)$ for those who take the detour is:

$$(X \cdot G)_B = x \cdot (q - \Delta t - \frac{\Delta p}{k}) \cdot (\Delta t \cdot k + \Delta p)$$

$$= \ x \cdot \left(q \cdot \Delta t \cdot k + q \cdot \Delta p - \Delta t^2 \cdot k - \Delta t \cdot \Delta p - \Delta t \cdot \Delta p - \frac{(\Delta p)^2}{k}\right)$$

$$= x \cdot (\ q \cdot \Delta t \cdot k + q \cdot \Delta p - \Delta t^2 \cdot k - 2\Delta t \cdot \Delta p - \frac{(\Delta p)^2}{k})$$

The total increase in generalized costs for those who wait and those who take the detour are per incident:

$$(X \cdot G)_A + (X \cdot G)_B$$

$$= x \cdot \frac{k}{2} \cdot \left(\Delta t + \frac{\Delta p}{k}\right)^2 + x \cdot \left(\ q \cdot \Delta t \cdot k + q \cdot \Delta p - \Delta t^2 \cdot k - 2\Delta t \cdot \Delta p - \frac{(\Delta p)^2}{k}\right)$$

$$= \frac{x}{2} \cdot (\Delta t^2 \cdot k + \frac{\Delta p^2}{k} + 2\Delta t \cdot \Delta p) + x \cdot \left(\ q \cdot \Delta t \cdot k + q \cdot \Delta p - \Delta t^2 \cdot k - 2\Delta t \cdot \Delta p - \frac{(\Delta p)^2}{k}\right)$$

$$= x \cdot (\frac{\Delta t^2 \cdot k}{2} + \frac{\Delta p^2}{2k} + \Delta t \cdot \Delta p) + x \cdot \left(\ q \cdot \Delta t \cdot k + q \cdot \Delta p - \Delta t^2 \cdot k - 2\Delta t \cdot \Delta p - \frac{(\Delta p)^2}{k}\right)$$

$$= x \cdot (\frac{1}{2} \cdot \Delta t^2 \cdot k + \frac{1}{2} \cdot \frac{\Delta p^2}{k} + \Delta t \cdot \Delta p + q \cdot \Delta t \cdot k + q \cdot \Delta p - \Delta t^2 \cdot k - 2\Delta t \cdot \Delta p - \frac{(\Delta p)^2}{k})$$

$$= x \cdot (-\frac{1}{2} \cdot \Delta t^2 \cdot k - \frac{1}{2} \cdot \frac{\Delta p^2}{k} - \Delta t \cdot \Delta p + q \cdot \Delta t \cdot k + q \cdot \Delta p)$$

$$= x \cdot [\Delta t\left(q \cdot k - \Delta p - \frac{\Delta t \cdot k}{2}\right) + \Delta p\left(q - \frac{\Delta p}{2k}\right)]$$

$$= x \cdot [-\frac{1}{2k}(k\Delta t + \Delta p)(k\Delta t + \Delta p - 2kq)]$$

The total increase in generalized costs per year for those who wait and those who take the detour when $(\Delta t \cdot k + \Delta p) < q \cdot k$, are denoted R_d:

$$R_d = H \cdot [(X \cdot G)_A + (X \cdot G)_B] = H \cdot \ x \cdot [-\tfrac{1}{2k}(k\Delta t + \Delta p)(k\Delta t + \Delta p - 2kq)] \quad \text{(A.4)}$$

Sensitivity for the economic loss $[(\boldsymbol{X} \cdot \boldsymbol{G})_{\boldsymbol{A}} + (\boldsymbol{X} \cdot \boldsymbol{G})_{\boldsymbol{B}}]$:

$\frac{d[(\boldsymbol{X}\cdot\boldsymbol{G})_{\boldsymbol{A}}+(\boldsymbol{X}\cdot\boldsymbol{G})_{\boldsymbol{B}}]}{d\Delta p} = -\frac{1}{k}x(k\Delta t + \Delta p - kq) > 0$ since $(k\Delta t + \Delta p - kq) < 0$

$\frac{d[(\boldsymbol{X}\cdot\boldsymbol{G})_{\boldsymbol{A}}+(\boldsymbol{X}\cdot\boldsymbol{G})_{\boldsymbol{B}}]}{dk} = \frac{1}{2k^2}x(-k^2\Delta t^2 + 2qk^2\Delta t + \Delta p^2) > 0$ if $(2qk^2\Delta t + \Delta p^{2)} > k^2\Delta t^2$

$\frac{d[(\boldsymbol{X}\cdot\boldsymbol{G})_{\boldsymbol{A}}+(\boldsymbol{X}\cdot\boldsymbol{G})_{\boldsymbol{B}}]}{dq} = x(k\Delta t + \Delta p) > 0$

$\frac{d[(\boldsymbol{X}\cdot\boldsymbol{G})_{\boldsymbol{A}}+(\boldsymbol{X}\cdot\boldsymbol{G})_{\boldsymbol{B}}]}{dx} = -\frac{1}{2k}(k\Delta t + \Delta p)(k\Delta t + \Delta p - 2kq) > 0$ since $(k\Delta t + \Delta p - kq) < 0$ and $(k\Delta t + \Delta p - 2kq) < (k\Delta t + \Delta p - kq)$

$\frac{d[(\boldsymbol{X}\cdot\boldsymbol{G})_{\boldsymbol{A}}+(\boldsymbol{X}\cdot\boldsymbol{G})_{\boldsymbol{B}}]}{d\Delta t} = -x(k\Delta t + \Delta p - kq) > 0$ since $(k\Delta t + \Delta p - kq) < 0$