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# The impact of flooding on road transport: A depth-disruption function

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ABSTRACT

Transport networks underpin economic activity by enabling the movement of goods and people. During extreme weather events transport infrastructure can be directly or indirectly damaged, posing a threat to human safety, and causing significant disruption and associated economic and social impacts. Flooding, especially as a result of intense precipitation, is the predominant cause of weather-related disruption to the transport sector. Existing approaches to assess the disruptive impact of flooding on road transport fail to capture the interactions between floodwater and the transport system, typically assuming a road is fully operational or fully blocked, which is not supported by observations. In this paper we develop a relationship between depth of standing water and vehicle speed. The function that describes this relationship has been constructed by fitting a curve to video analysis supplemented by a range of quantitative data that has be extracted from existing studies and other safety literature. The proposed relationship is a good fit to the observed data, with an R-squared of 0.95. The significance of this work is that it is simple to incorporate our function into existing transport models to produce better estimates of flood induced delays and we demonstrate this with an example from the 28th June 2012 flood in Newcastle upon Tyne, UK.



## 1. Introduction

Infrastructure networks are often considered to be the backbone of cities. Ensuring their resilience, has become a vital aspect of governing and managing an economically-viable and liveable city. In particular, transport networks support the safety and wealth of communities, especially in the context of a global economy increasingly reliant on the mobility of goods, information and people (Rodrigue and Notteboom, 2013). Changes in the climate, rapid urbanisation, and increased infrastructure interdependence are putting societies, assets, and the built environment under increasing pressure. This is particularly evident in urban areas when transport systems are affected by weather-related hazards.

Flooding, especially flash flood events that start rapidly as a result of intense precipitation, is the predominant cause of weather-related disruption to the transport sector (DfT, 2014a) and this is expected to continue into the future (Dawson et al., 2016). This problem is particularly acute on the road network in urban areas owing to the high proportion of impermeable surfaces that prevent the infiltration of water into the soil. Heavy rain causes overland flow that can result in drains

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exceeding their capacity, and increasing the likelihood they become blocked by debris, before flood warnings can be widely disseminated. The relationship between adverse weather, traffic flow and congestion is acknowledged but poorly understood (Pyatkova et al., 2015; Hooper et al., 2014; Tsapakis et al., 2013; Koetse and Rietveld, 2009; Suarez et al., 2005).

On the 28th June 2012, 50 mm rain fell on Newcastle upon Tyne (UK) between 3 and 5 pm, a time typically associated with heaving commuting and school collection traffic (Newcastle City Council, 2013). This is similar to the average monthly total, and a return period of 1 in 100 years. Most public transport was cancelled, some roads were completely impassable whilst others experienced very slow running traffic for many hours (Fig. 1). Drivers reportedly abandoned their cars and some ran out of fuel after several hours of slow movement. The event flooded more than 1200 homes and caused £8m of direct damage to roads and pavements alone.

Reliable transport systems are valued for their safety, cost, travel time, and regularity of service (Koetse and Rietveld, 2009). Maintaining the volume traffic flow on the network, whether public transport or private travel, is fundamental for production, logistics, and business (Jenelius et al., 2006). Flooding impacts this in a number of ways through both direct impacts (*e.g.* physical damage to transport infrastructure) and indirect impacts (*e.g.* disruption to traffic flow, business interruption, increased emissions) (Brown and Dawson, 2016; Hammond et al., 2015; Walsh et al., 2012). Although direct damages could be consistent (USACE, 2009), the reduction in performance of transport systems due to flooding is the most detrimental factor for the society and it has been estimated at around £100 k per hour for each main road affected (Arkell and Darch, 2006; Hooper et al., 2014). Meanwhile, studies have shown that roads are among the first cause of deaths in cities during flooding, due to vehicles being driven through flooded roadways (Jonkman and Kelman, 2005; Fitzgerald et al. 2010; Drobot et al., 2007).

### 1.1. Flood risk analysis

The concept of risk can have a different interpretation according to the context in which it is considered (*e.g.* economic, environmental, social). A full review of flood risk definitions has been undertaken by Gouldby et al. (2005). This study considers flood risk as the product of the flooding probability and the consequences (Hall et al., 2003). In this definition consequences account for exposure (*i.e.* the people, assets and activities, threatened or potentially threatened by a flood) and vulnerability (*i.e.* physical, social, economic, and environmental factors or processes, which increase susceptibility to a flood). More formally, flood risk (r) can be calculated as a function of the probability of an event or hazard ($\rho$) and the consequences or impacts of that event ($d$) for a set of input conditions, defined by the vector $\mathbf{x}$: = $\{x_1, x_2, \ldots, x_n\}$, where each variable $x_i$ represents a particular property of the flooding system (Dawson and Hall, 2006):

$$r = \int^{\rho}(\mathbf{x})d(\mathbf{x})d\mathbf{x} \qquad (1)$$

To assess the impacts of damage to buildings, there are well established functions (damage functions) that relate depth of flooding ($w$) with consequent damage, *i.e.* a flood risk calculation only interested in properly damage would replace $d$(x) in Eq. (1) with the function $d(w)$. These functions are derived by integrating information from past flood events and building

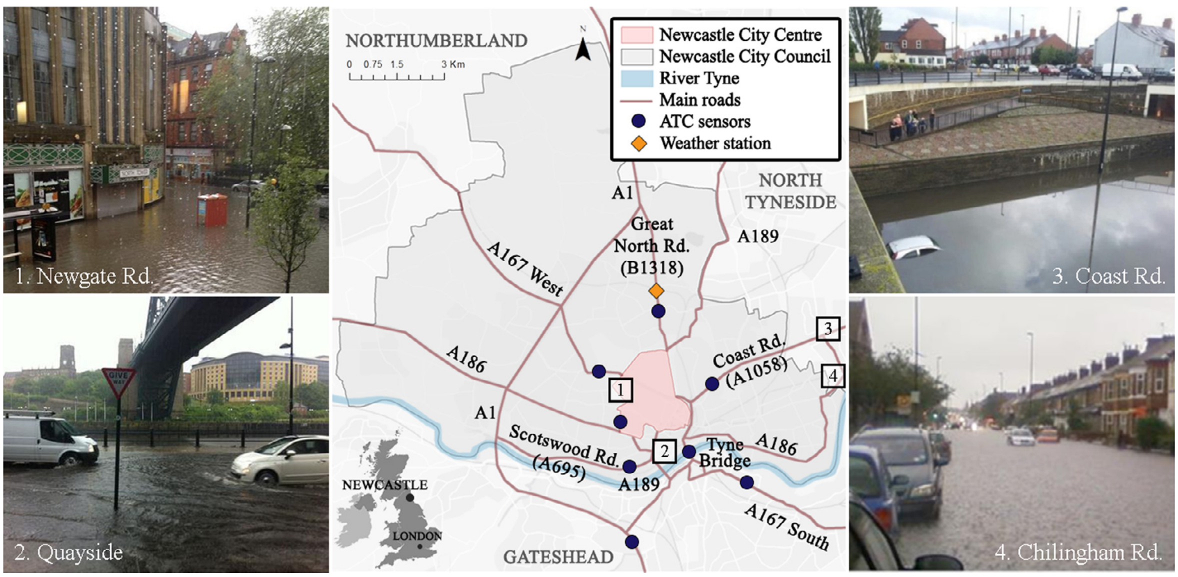


**Fig. 1.** Newcastle City Council boundary, and some indicative photos from the 2012 flood. Photos are from a Newcastle University website, set up the day after the flood to allow people to upload photos and observations: http://ceg-morpethflood.ncl.ac.uk/toonflood.

survey data (Penning-Rowsell et al., 2013), hence they are highly regional-dependent (*e.g.* accurate analysis need to be done before applying function that were developed for a specific area in another context). Functions have also been developed for structural damage of infrastructure (Dutta et al., 2003; Scawthorn et al., 2006; Jonkman et al., 2008a, 2008b; Hammond et al., 2015; Kellermann et al., 2016) or direct damages to vehicles (USACE, 2009). Similarly, functions that relate flood depth to mortality rate have also been constructed (Jonkman and Kelman, 2005; Jonkman et al., 2008a, 2008b). These functions are relevant to understand 'ultimate limit state' whereas many flood impacts are better characterised by a 'serviceability limit state' failure where performance of the infrastructure system is reduced.

### *1.2. Appraising the impacts of flood disruption*

Existing approaches to assessing the impact of flooding on transport disruption do not capture the complexity of interactions between the flood hazard and transport system. Typically, assumptions can include (TRB, 2010; Environmental Agency, 2010; Shand et al., 2011; Penning-Rowsell et al., 2013; DfT, 2014b):

- traffic volumes and speeds are assumed to correspond to regional (or even national) average statistics;
- a road is assumed to be completely closed when its crown is covered by water, regardless of depth;
- traffic on open roads continues to flow smoothly, perhaps at a slightly reduced maximum speed;
- traffic volumes do not exceed the design capacity of a road;
- traffic conditions do not change over the course of the day, or seasonally; and,
- diversion routes, and changes (or not) to driver behaviour as a result of the flood, are often assumed without any clear rationale.

These assumptions are increasingly inappropriate in urban areas, where traffic conditions are most dynamic, and where topographic and manmade features mediate flow paths leading to multiple flooded locations and a range of flood depths. If a passable road is defined in terms of the crown of the road being covered by water, the range of flood depths could be huge. Assuming a lane width of 2.7–3.7 m and a potential crossfall of 1.25–6% (Bartlett, 2013) this gives a possible range of threshold flood depth of 3.4–22.2 cm. Moreover, there is substantial evidence that roads can be, and often are, used by drivers even if flooded.

To better understand the impacts of flooding on road traffic disruption, this paper undertakes a systematic review of empirical, simulation and experimental studies of the impacts of extreme weather on transport disruption. Subsequently, by synthesising across these multiple sources a function has been developed, that to the best of the authors' knowledge, for the first time relates flood depth to traffic speed. This provides a significant advance on existing approaches to considering the impact of flooding on transport disruption that use granular, or averaged, assumptions about traffic flows and flood depths. Finally, the implications, uncertainties and emerging opportunities to improve this function are considered.

## 2. Weather disruption of road transport

A number of studies over the last decade have looked at weather impacts on road networks, including several broad reviews (Martínez-Gomariz et al., 2016; Kramer et al., 2016; Faturechi and Miller-Hooks, 2015; Hammond et al., 2015; Jaroszweski et al., 2014; Koetse and Rietveld, 2009) that consider aspects of the relationship between transport sector and climate hazards. However, this paper is distinct from these reviews with its focus on the impact of flooding on traffic flows and network performance, considered in 'functional' terms (*i.e.* travel time, flows, accessibility). Furthermore, this is distinct to the 'topological' and more abstract measures used in network modelling studies (*e.g.* Albert and Barabasi, 2002; Dunn and Wilkinson 2013; Lhomme et al., 2013). The review draws from the papers that couple analysis of transport and weather (including snow, ice, rain, fog, wind, heat). These studies cover small (*e.g.* road-vehicle interactions) and large scale (*e.g.* city-wide impacts of weather) analysis. The literature is summarised in Table 1 and includes (i) observations and data from extreme weather events; (ii) modelling and simulation studies; and, (iii) experimental studies that provide evidence of the impacts of water on vehicle performance.

The review revealed a significant body of work that relates weather and transport. However, these studies are typically focused on particular circumstances or geographies with limited consideration of transferability or generalisation. Drawing together various data from observational, modelling and experimental sources has enabled the production of a function that relates depth of flooding to speed reduction. This study focuses on the reduction of vehicle speed, to ensure safe trafficability, in the presence of floodwater on road links. This includes consideration of both the 'roadworthiness' of vehicles in flood conditions, which is affected by their design including, for example, the heights of air inlets, as well as their 'stability', which in this case is dominated by aquaplaning, but could also include floating, sliding and tipping (Kramer et al., 2016).

### *2.1. Observational analysis*

A number of observational studies collate, and analyse, information on vehicle movement and local weather conditions. Studies have taken a range of approaches to categorise weather conditions. For example, Tu et al. (2007) investigated travel

**Table 1**
Overview of the most recent research considered in the study, organized in three categories.

| Author | Country | Hazard(s) | Brief summary |
|---|---|---|---|
| **Observational studies** | | | |
| Agarwal et al. (2005) | USA | Rainfall<br>Snowfall | Study on the impact from weather to speed reductions (up to 7% for heavy rain and 15% for heavy snow), due to snowfall or rainfall, for an urban freeway in Minneapolis. |
| Andrey et al. (2003) | Canada | Rainfall<br>Snowfall | Focus on weather-related accidents, exploring road safety in adverse conditions for snowfall and rainfall events over a four-year period (1995–1998) for six cities. Adverse weather resulted in an increase of 75% in the number of collisions, as compared to normal conditions. |
| Chung (2012) | Korea | Rainfall | Estimation of the total delay to road traffic caused by rainfall, combining weather information and traffic flow data from 2008. The relationship is expressed as average non-recurrent congestion (vehicles-hrs/km) vs rainfall (mm/hr). Rainfall is considered in a discrete range of five categories, from negligible to warning. |
| Hooper et al. (2014) | UK | Rainfall | Detailed analysis regarding the relationship between rainfall intensity and vehicle speed on UK roads. A clear threshold between speeds with no precipitation and the speed when it is raining can be identified, but such relationship was shown as a complex one that requires more research. A mathematical relationship between rainfall intensity and vehicle speed is not defined. |
| Hooper et al. (2013) | UK | Rainfall | Observations about the impacts from precipitation on speed and flow for a UK motorway, including road type and congestion. |
| Hranac et al. (2006) | USA | Rainfall<br>Snowfall | Study about the impact of precipitation on macroscopic traffic in three cities (Minneapolis, Baltimore and Seattle), considering two categories for each hazard (light/heavy rain and snow). Rainfall resulted to impact flows by reducing free-flow speed up to 9%. |
| Ibrahim and Hall (1994) | Canada | Snowfall | Statistical interpretation of traffic and weather datasets, from permanent traffic counters and weather stations in Alberta (2005–2009). Heavy rain resulted to reduce capacity up to 15%. Only rainfall considered, not flooding. |
| Kyte et al. (2001) | USA | Ice<br>Rainfall<br>Snowfall<br>Visibility<br>Wind | Analysis about the effect environmental factors (wind speed, precipitation intensity, visibility and pavement condition) on free-flow traffic speed. Intensity is defined by a discreet range (*e.g.*: 1 = none, 2 = light, 3 = medium, 4 = heavy). |
| Martin et al. (2000) | USA | Rainfall<br>Snowfall | Examination of signal timing in adverse weather conditions in Salt Lake City, collecting local traffic flow data over the winter 1999–2000 to determine traffic trends during peak hours. Free flow speed decreased by 10% during rainfall events. |
| Sabir et al. (2008) | Netherlands | Rainfall<br>Snowfall<br>Temperature<br>Wind | Estimation of commuter costs due to adverse weather on traffic speed, through a regression model. The commuting cost due to rainfall seemed to increase up to 15%, and up to 7% for snowfall. |
| Smith et al. (2004) | USA | Rainfall | Study of the impact of rainfall on free flow speed with the intensity of rainfall as a continuous variable. Data was collected in Virginia, and the percentage of speed reduction considered as a function of the intensity. |
| Stern et al. (2003) | USA | Rainfall<br>Visibility<br>Wind | Assessment of travel delay impacts of weather along specific roadway segments around metropolitan Washington D.C. (1999–2001). Meteorological data, in four categories of intensity, were coupled with travel time data, resulting in travel time increase of average 14%. |
| Tsapakis et al. (2013) | UK | Rainfall<br>Snowfall<br>Temperature | Study of the impact of weather conditions on macroscopic urban travel times and speed in Greater London area. The impact of adverse weather on the network is investigated during different times of the day (morning, noon, evening) and for multiple parts of the area (central London, inner, outer), comparing travel times under normal and perturbed conditions. Again, only intensity of precipitation is included, not flooding effects. |
| Tu et al. (2007) | Netherlands | Ice<br>Fog<br>Rainfall<br>Snowfall | Empirical investigation of the impacts of adverse weather on travel time variability on the basis of a large database of travel times alongside weather data of rain, snow, ice fog and storm in Delft. It was found that adverse weather leads to higher travel time variability. A binary hazard is considered (*e.g.* normal or hazardous). |
| USACE (2009) | USA | Flooding | The study advances guidance for the use of vehicle depth-damage curves in the USA. These curves are relate to physical damages to vehicles only, and are determined using post-event surveys of vehicles assessment |
| **Modelling studies** | | | |
| Arrighi et al. (2015) | – | Flooding | Focus on the description of the incipient motion stationary cars during floods, using a 3D numerical model to assess the contribution of drag and lift forces. |
| Chang et al. (2010) | USA | Flooding | Integrated impact assessment methods involving hydraulic simulations and travel forecasting, with a case study in Portland (Oregon). An integrated framework of climate change on urban flooding and transport sector was advanced, including hydrologic modelling and dynamic traffic assignment. The focus is in particular on the hours delay experienced by vehicles and on road closure as main effect from flooding, with only complete closure of links considered. |
| Dalziell and Nicholson (2001) | New Zealand | Ice<br>Earthquake<br>Snowfall<br>Volcanic eruptions | Risk and impact of natural hazards (excluding flooding) on road networks. In particular, it investigates the effect of road closures on traffic flows through a traffic assignment model based of the least-cost path. |
| Gallaway et al. (1979) | – | Wet surfaces | Experimental derivation of a regression relationship for planar road surfaces between hydroplaning parameters (such as spin down, tyre inflation pressure, tread depth, water depth and mean texture depth) and vehicle speed. |

**Table 1** (*continued*)

| Author | Country | Hazard(s) | Brief summary |
|---|---|---|---|
| Ong and Fwa (2008) | – | Wet surfaces | Discussion about numerical hydroplaning simulation model and evaluation of hydroplaning risk with surface groove deterioration, in a more mechanistic manner. Aquaplaning rarely occurs below 72 km/h (55 mph). |
| Penning-Rowsell et al. (2013) | UK | Flooding | Good practices for appraising flood risk management, in particular for road disruptions (road is assumed closed when "the crown of the road is covered by water") and losses due to longer (in time and/or space) travelling. Multiple transport modelling approaches are presented, for impact assessment on transport network. |
| Pyatkova et al. (2015) | Caribbean | Flooding | The study integrated a flood and a transport model to study the interruptions of roads due to flood propagation. Although the methodology is holistic and advances, no rational is behind the threshold of 20 cm that determine roads as trafficable or not. Thus, the model is limited to the binary representation of inundated roads. |
| Sohn (2006) | USA | Flooding | Analysis about the identification of critical links of transport network affected by flooding, using purely topological measures. An accessibility score was derived in order to quantify the potential impact of flood damage on the state transportation system, on the distance and traffic volume criteria. |
| Suarez et al. (2005) | USA | Flooding | Simulation modelling of climate change on Boston Metro Area, looking at land use, demography and climate within urban transportation system. The estimation of the impact is through a model able to simulate flows under 12 different flooding scenarios, run for the contemporary year (that was 2003) and a future time (2025). However, there is a simplistic consideration of roads intersecting floods (*i.e.* road capacity equal to zero if intersecting with floods, and trips no longer generated from flooded areas). |
| Teo et al. (2013) | – | Flooding | Numerical model to assess the hydraulic behaviour and safety degree of vehicles during flood, using hydrodynamic models of parked cars. |
| Yin et al. (2016) | China | Flooding | A 2D inundation modelling is coupled to a transport model to assess the potential impact of pluvial floods on road networks in Shanghai. Transport disruption is defined as "road closure", thus the study is limited to a binary approach determined by a critical threshold of 30 cm. |
| **Experimental studies** | | | |
| Kramer et al. (2016) | – | Flooding | In order to determine the safety criteria of trafficability during flood events, flume experiments were conducted on prototype die-cast models of vehicles. Results recommended a safety threshold of fording depths of 0.3 m for passenger cars (VW Golf) and 0.6 m for emergency vehicles (such as auto-ambulances). |
| Martínez-Gomariz et al. (2017) | – | Flooding | The study developed a stability coefficient for vehicles exposed to flooding. Effects of both friction and buoyancy were analysed by conducting experiments with 12 different car models, using three scales. Results enabled to define a stable area in the flow depth-velocity domain for parked vehicles in flood waters. |
| Shand et al. (2011) | – | Flooding | Based on previous experimental and analytical data (*e.g.* Gallaway et al., 1979), criteria for stationary vehicle stability are proposed for three vehicle classes (small, large and 4WD cars). |
| Shu et al. (2011) | – | Flooding | Formula for incipient velocity for scaled models of cars, in partially submerged conditions (Ford Focus, Volvo XC90, Ford Transit). |
| Onishi et al. (2014) | – | Flooding | Studies on initial floating condition of partially submerged cars, considering flow velocity and water depth and a range of vehicle orientations relative to the floodwater. |
| Teo et al. (2012) | – | Flooding | Study on stationary scaled die cast model vehicles (Mini Cooper, Ford Escort, Mitsubishi Pajero, BMW X5), looking at the degree of hydraulic stability for vehicles. |
| Toda et al. (2013) | – | Flooding | Study on initial floating condition of partially submerged cars (scaled sedan and minivan) by hydraulic experiments, considering flow velocity and water depth. |
| Xia et al. (2011) | – | Flooding | Formula to model the initial velocity of flooded cars, on the basis of the vehicle mass and dimensions, buoyancy and drag forces. Laboratory experiments were run for three types of scaled cars (Mini Cooper, Mitsubishi Pajero, BMW X5), considered fully-submerged. |
| Xia et al. (2014) | – | Flooding | Study on stability criterion, including multiple ground slopes and vehicle orientation angles, for partially submerged vehicles (Honda Accord and Audi Q7). A mechanics-based formula was derived and tested using empirical data obtained from two types of die-cast vehicles. |
| Xia et al. (2016) | – | Flooding | Study on hydrodynamic impacts of vehicle blockage at bridge sites using scaled physical river model and scaled vehicles (Mini Cooper, Ford Escort, Mitsubishi Pajero, BMW X5). |

time reliability on the basis of a large database of travel times, but weather was considered to be either "normal" or "adverse". Much research discretises rainfall intensity into a number of bins, reporting vehicle speeds as a function of these categories (Ibrahim and Hall, 1994; Kyte et al., 2001; Smith et al., 2004; Agarwal et al., 2005; Hranac et al., 2006; Chung, 2012). Other studies adopted a similar approach to discretisation to study wind and visibility (Stern et al., 2003) and snowfall (Tsapakis et al., 2013).

Some recent studies have sought to overcome the discrete approach by looking for correlations between speed, traffic flow, and precipitation. A linear regression of traffic speed and precipitation by Hooper et al. (2014) showed an identifiable, but weak, relationship. This was advanced also at an earlier date in Hooper et al. (2013) by considering additional factors such as road type and congestion. Nevertheless, both studies were focused on precipitation data and for one motorway corridor only. Sabir et al. (2008) also proposed a regression model that relates speed reduction due to adverse weather (temperature, rain, snow and wind) to commuting costs, whilst Andrey et al. (2003) correlate road safety and accident data against hourly observations of rainfall and snowfall. These studies recognise that correlations between weather and disruption are complex as they relate to road network capacity, drainage systems and a number of other factors. Flooding is not considered in these studies.

### 2.2. Modelling and simulation analysis

Modelling and simulation tends to be either focused on small scale vehicle-water interactions, or transport network scale analysis. Moore and Power (2002) used a dam break model to assess the safe distance of a road from an offstream water supply storage (or ring tank). Teo et al. (2013) uses a hydrodynamic model to simulate the impact of floodplain flow on vehicles in the Muar river basin in Malaysia. Arrighi et al. (2015) use a detailed 3D simulation of the interactions between motion of flood water around vehicles and to systematically estimate the forces, including drag, acting on the vehicle. Although these detailed simulations provide a better understanding of hydrodynamics forces, no investigation involved study of vehicles in motion.

This scale of analysis is in contrast to work by Dalziell and Nicholson (2001) which uses a probabilistic approach to assess the risk of road closures due to various weather events, although not from flooding. Chang et al. (2010), Suarez et al. (2005) couple hydrological and traffic modelling to analyse vehicle delays and consider multiple scenarios and possible climate impacts. These approaches assume that flooding of a road makes it impassable. Sohn (2006) analysed the significance of highway network links under flood damage, deriving a composite accessibility index of two factors, distance and traffic volume.

A particular type of modelling study focuses on analysing vehicle stability from theoretical principles. The critical hydroplaning (also referred to as aquaplaning) speed threshold for grooved pavement (like asphalt) has been studied with models first advanced by Horne (1968), and further developed by Stocker et al. (1974) and Gallaway et al. (1979). Hydroplaning occurs when a loss of traction prevents the vehicle in motion from responding to control, and is calculated using a multi-parameter regression function that includes spin down, tyre inflation pressure, tread depth, water depth and mean texture depth. Ong and Fwa (2008) derived a simplified version of the hydroplaning equation, assuming smooth tyres, locked wheel condition, null surface texture effect and a typical pressure for a passenger car (206 Kpa, *i.e.* 30 PSI):

$$v_p = \frac{67.68}{t_w^{0.06}} + 18.76 \tag{2}$$

where $v_p$ is the hydroplaning speed in km/h; $t_w$ the water-film thickness in mm over a range of 1–10 mm. For a film of 10 mm the associated hydroplaning speed is 77 km/h. Dynamic hydroplaning (when a moving tyre is completely separated from the pavement by a layer of water) occurs at high speed (above 72 km/h, 45 mph) with water ponds depth of at least 2.5 mm (Kumar et al., 2012). Indicative breaking distance for wet roads are provided in driving guidance, including the British Highway Code (DfT, 2016), but these are not related to water depth.

### 2.3. Experimental analysis

Experimental studies usually focus on the stability of parked vehicles for a range of flood depths and have provided some of the earliest analysis (Bonham and Hattersley, 1967; Gordon and Stone, 1973) to determine the depth and velocity required for a vehicle to float or slide. However, as a result of changes in modern vehicle design, those experimental works are now of limited value (Shand et al., 2011). More experimental studies by Xia et al. (2011), Shu et al. (2011) and Xia et al. (2014) have investigated the behaviour of parked cars in flooded streets and subjected to water forces, looking at the incipient motion velocity as a criterion of stability in flood conditions. More recent experimental work by Toda et al. (2013), Teo et al. (2012), Onishi et al. (2014) and Martínez-Gomariz et al. (2017), undertook further experimental study to explore a wider range of issues such as the threshold of vehicle instability, the effects of vehicle orientation, ground gradient, and consideration of the effects of buoyancy decrease from water inside the vehicle. Other studies have considered the interaction of vehicles with other infrastructure, such as bridges, revealing how vehicles related blockages can significantly alter flood flow paths and depths (Xia et al., 2016). A comprehensive summary of experimental studies is provided in Martínez-Gomariz et al. (2016), but as noted by Shand et al. (2011) such studies are limited to parked cars moved by water flows. Investigating vehicles in motion endangered by stagnated flooding is the focus of this review.

### 2.4. Summary

The literature highlighted substantial amounts of research into the impact of a wide range of natural hazards, including snow, ice, rain, fog, wind and heat, on transport disruption. These studies span events of different spatial scale and magnitude, and include results from a number of different countries. Rainfall intensity has repeatedly been shown to be a factor in transport disruption, but the correlation is not always strong. Rainfall can reduce driver visibility, and many drivers may reduce speeds as a precautionary measure. However, measuring only rainfall does not take into account where the water falls, its flow paths, and where it pools sufficiently deeply to block a road. Whereas there are many observational studies that consider rainfall, most of the evidence that looked at flooding was from experimental and modelling studies.

Data from a range of observational, experimental and modelling studies contributes to the understanding aspects of the impact of flooding on traffic disruption. Whilst some studies have sought to understand water vehicle interactions, others analysed impacts at the scale of whole networks or city-region. Collectively, the literature shows there are many uncertainties that mediate the impact of flooding on disruption, including transport system properties, such as road type and capacity, road network structure, vehicle type, and the flood event properties, such as spatial extent, flood depth and velocity (during flash floods, for example, water levels rise rapidly meaning it is more likely that a vehicle is swept away rather than affected by water entering the vehicle).

No modelling study is able to capture the breadth of variability in these factors and, in line with other flood risk assessment approaches (Merz et al., 2010; De Moel and Aerts, 2011; Jonkman and Dawson, 2012), reflecting and analysing these uncertainties is crucial. The next section of this paper draws together findings from the literature to develop an empirical function relating flood depth to vehicle speed, in the particular case of stagnated water.

## 3. A depth-disruption function

Models in the literature, and current appraisal guidance, assume a road is either open or closed. Yet observations from flooding events, such as the June 2012 event in Newcastle, have shown that flooding on a road does not necessarily preclude people from driving along it. There is therefore a need to build a more robust relationship, improving current simulations. Whilst there are a number of studies that look into the stability of parked vehicles, these relationships do no hold for vehicles that are driving (Shand et al., 2011).

It is infeasible to have precise knowledge of every vehicle-floodwater interaction over a transport system of any realistic scale. Development of empirical relationships to describe the performance of vulnerability or fragility curves provides a means of capturing a large number of uncertainties and enabling broad scale infrastructure risk analysis (Dawson and Hall, 2006; Merz et al., 2010; Dunn et al., 2015). In order to transition from a binary view of a flooded road being considered 'open' or 'closed', a curve that relates the depth of floodwater to a reduction in vehicle speed has been created by integrating data from the literature reviewed previously, and some other sources of data. This 'depth-disruption' function is presented in Fig. 2.

The choice of appropriate flood metric to assess impact varies according to sector: one parameter might be significant for damage evaluation of residential buildings, for example, but less important for agricultural crops or infrastructure (Merz et al., 2010). A number of indicators can be taken as intensity measures (IMs), including: flood duration, flow velocity, rate of water rise, flood preparedness, sediment, pollution, and others (Merz et al., 2010; Kreibich et al., 2009; Merz and Thieken, 2009; Merz et al., 2004; Smith, 1994). Isolation of the influence of each variable is challenging because of insufficient data on their spatio-temporal dynamics during a flood. However, depth and velocity are considered to be the key metrics (Merz et al., 2010; Kreibich et al., 2009). Moreover, for indirect impacts (such as service and business interruption) most of these parameters have no significant influence, and it is considered reasonable to use water depth and flood duration as key measures for the magnitude and timeframe of impact respectively (Kreibich et al., 2009).

The risk of disruption from flooding, $r_d$, can be calculated by modifying Eq. (1), as shown in Eq. (3).

$$r_d = \tau \int^{\rho} (h) \cdot \sum_{i=1}^{N} (v - w_i(h) \cdot v(w_i)) dh \tag{3}$$

where $\rho(h)$, is the probability of rainfall $h$, which leads to a distribution of the maximum flood depths $w(h)$ along each journey $i$, $v$ is the speed allowed by transport regulations and $v(w)$ describes the speed as a function of flood depth. The total disruption for each rainfall is calculated by summing the impact across all $N$ journeys. The annual expected disruption is weighted according to the probability of each rainfall event, and can be converted to a cost by using an appropriate coefficient of the value of time ($\tau$) (DfT, 2014c).

### 3.1. Curve development

The function (Fig. 2) is derived by combining data from the experimental, observational and modelling studies reviewed. A function was fitted, to describe the limit vehicle speed, $v$, as a function of flood depth, $w$, which has an R-squared of 0.95:

$$v(w) = 0.0009w^2 - 0.5529w + 86.9448 \tag{4}$$

The speed $v(w)$ is the maximum acceptable velocity that ensures safe control of the vehicle given the depth of water (*i.e.* not considering non-flood related safety issues). Not every paper reviewed contains information that can be plotted on the figure because, as noted previously, much of the research has focused on extremities of the graph such as hydroplaning or the stability of parked vehicles. Information from the scientific literature has been augmented with additional data from video analysis and guidance from driver safety groups. The complete list of sources that are plotted, explaining each point of the curve, can be found in Table 2.

Unless otherwise stated this data relates to 2WD vehicles, however other vehicles may perform differently. For example, 4WD or off road vehicles have raised or watertight sensitive electronics and air intakes. This can allow safe driving in depths up to 45 cm, or even 90 cm. For smaller cars, some literature suggests that 15 cm depth may be sufficient to stall a car as

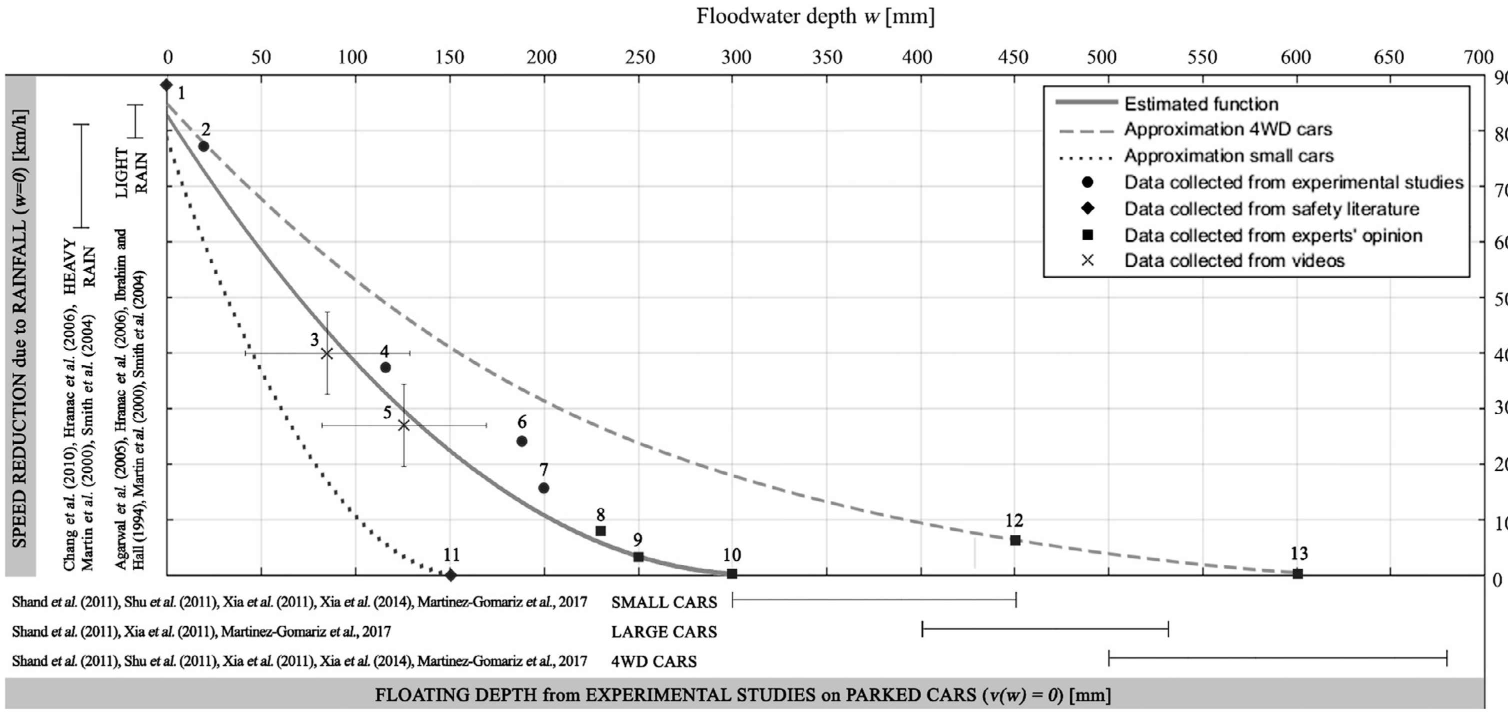


**Fig. 2.** The depth-disruption function that relates flood depth on a road with vehicle speed.

**Table 2**
Source details of each point of the curve, including sliding floodwater depth from studies on parked cars and speed reduction due to rain from empirical studies. Definition of "heavy" and "light" rain from Hranac et al. (2006) and Chung (2012).

| Point no. | Water depth (mm) | Vehicle speed (km/h) | Source | Notes |
|---|---|---|---|---|
| **Estimated function** | | | | |
| 1 | 0 | 88 | 1a. Morris et al. (2011)<br>1b. Chung (2012) | In unflooded conditions (i.e. water depth = 0 mm), speed reduction is considered due to other circumstances (as rainfall or wet pavement). |
| 2 | 10 | 77 | 2a. Gallaway et al. (1979)<br>2b. Ong and Fwa (2008) | Eq. (2) has been applied. |
| 3 | 87 | 40 | Youtube (2014) | Observation of a Ford S driving through a flooded road in Bromsgrove (UK) in 2014. |
| 4 | 116 | 37 | Galatioto et al. (2014) | Data obtained in the results. |
| 5 | 125 | 26 | Youtube (2012) | Observation of an Audi A3 driving through a flooded road in Perth (UK) in 2012 |
| 6 | 189 | 24 | Galatioto et al. (2014) | Data obtained in the results. |
| 7 | 200 | 16 | EVSTF (2015) | Water depth of 200 mm and vehicle speed of 10 km/h were considered as a reasonable and likely scenario for testing vehicle performance in flooding conditions. |
| 8 | 230 | 7 | 8a. English (2016)<br>8b. Greenflag.com | Supposing a depth of water as 1/3 of the tyre, speed of max 4 mph (7 km/h) is recommended. |
| 9 | 250 | 3 | Boyce (2012) | Puddles that can reach the undertray of the car should be crossed very slowly, as at 3 km/h. |
| 10 | 300 | 0 | 10a. English (2016)<br>10b. Gissing et al. (2016)<br>10c. Greenflag.com (2016)<br>10d. Kramer et al. (2016)<br>10e. Smart Driving (2016)<br>10 f. Pyatkova et al. (2015)<br>10 g. The AA (2016)<br>10 h. Yin et al. (2016) | 300 mm is the average depth at which a passenger vehicles starts to float, and therefore widely recognised as the ultimate thresholds for a safety drive for most of the common cars. |
| Bounds | | | | |
| 11 | 150 | 0 | Pearson and Hamilton (2014) | Around 150 mm, water washes into the air intake. |
| 12 | 450 | 8 | Bavarianmw.com | Wading depth of 450 mm up to a speed of 5 mph (8 km/h). |
| 13 | 600 | 0 | Kramer et al. (2016) | Maximum wading depth for special vehicles. |
| **X-axis** | | | | |
| Studies on older vehicles | | | | |
| – | na | 0 | Bonham and Hattersley (1967) | Large car (Ford Falcon) |
| – | na | 0 | Gordon and Stone (1973) | Small car (Morris Mini) |
| – | na | 0 | Keller and Mitsch (1993) | Small car (Suzuki Swift) |
| – | na | 0 | | Small car (Honda Civic) |
| – | na | 0 | | Small car (Ford Laser) |
| – | na | 0 | | Large car (Ford LTD) |
| – | na | 0 | | Large car (Toyota Corolla) |
| Recent studies | | | | |
| – | 387 | 0 | Martínez-Gomariz et al. (2017) | Small car (Mini Cooper) |
| – | 531 | 0 | | Large car (Bentley Continental GT) |
| – | 686 | 0 | | 4wd (Mercedes G55 AMG) |
| – | 300 | 0 | Shand et al. (2011) | Small car |
| – | 400 | 0 | | Large car |
| – | 500 | 0 | | 4wd car |
| – | 450 | 0 | Xia et al. (2014) | Small car (Honda Accord) |
| – | 670 | 0 | | 4wd (Audi Q7) |
| – | 360 | 0 | Xia et al. (2011) | Small car (Mini Cooper) |
| – | 480 | 0 | | Large car (BMW X5) |
| – | 550 | 0 | | 4wd (Mitsubishi Pajero) |
| – | 570 | 0 | Shu et al.(2011) | Small car (Ford Focus) |
| – | 630 | 0 | | 4wd (Volvo XC90) |
| – | 580 | 0 | | van |
| **Y-axis** | | | | |
| Light rain (0.25–6.4 mm/h) | | | | |
| – | 0 | 81 | Chang et al. (2010) | Speed reduction: 8.2% |
| – | 0 | 79–85 | Smith et al. (2004) | Speed reduction: 4–10% |
| – | 0 | 80–83 | Hranac et al. (2006) | Speed reduction: 6–9% |
| – | 0 | 79 | Martin et al. (2000) | Speed reduction: 10% |

(continued on next page)

**Table 2** (*continued*)

| Point no. | Water depth (mm) | Vehicle speed (km/h) | Source | Notes |
|---|---|---|---|---|
| Heavy rain (>6.4 mm/h) | | | | |
| – | 0 | 75–76 | Ibrahim and Hall (1994) | Speed reduction: 14–15% |
| – | 0 | 62–66 | Smith et al. (2004) | Speed reduction: 25–30% |
| – | 0 | 81 | Martin et al. (2000) | Speed reduction: 25% |
| – | 0 | 76–81 | Hranac et al. (2006) | Speed reduction: 8–14% |
| – | 0 | 75 | Agarwal et al. (2005) | Speed reduction: 15% |

water can wash into the air intake (Kramer et al., 2016; Pearson and Hamilton, 2014). These values are used to identify "lower" and "upper" bounds to the curve to reflect the variability in the fleet. Unlike the central curve, there is insufficient data to fit the upper and lower curves. Therefore, the limited points were used to stretch the curve accordingly. Given sufficient information car fleet composition, it would be possible to reflect this within an impact assessment by adopting the appropriate percentage of different vehicles. Without this information, it is only recommended to use these lower and upper curves to provide indicative estimates of uncertainty. Other uncertainties are from factors unrelated to flood depth, such as tyre pressure, road pavement, behaviour of the driver, visibility, etc. which may be considered in more detail if sufficient data is collected.

The analysis on the x-axis (floating depth from experimental studies on parked cars) draws from studies of the impact of floodwater on parked cars and the depth at which they slide, tilt or float. This shows a large range that is influence by factors such as vehicle size and other assumptions about the relative orientation of the vehicle to the velocity of floodwater (Shand et al., 2011; Shu et al., 2011; Xia et al., 2011; Xia et al., 2014; Martínez-Gomariz et al., 2016). In these studies, 'small cars' includes passenger cars such as the Ford Focus, Mini Cooper and Honda Accord, whilst 'large cars' includes the BMW M5, and '4WD vehicles' includes the Pajero, Volvo XC90 and Audi Q7 (Table 2). Vans or trucks are not included.

The function intersection of the y-axis is influenced by studies (Ibrahim and Hall, 1994; Martin et al., 2000; Smith et al., 2004; Agarwal et al., 2005; Hranac et al., 2006; Chang et al., 2010; Pearson and Hamilton, 2014) of the impact of rainfall on vehicle speed, which can reduce driver visibility (Table 2). Speed reduction is different for light (0.25–6.4 mm/h) and heavy (>6.4 mm/h) rainfall.

### 3.2. Additional video analysis

Additional observations were obtained by analysing videos of cars driving along flooded roads. Flood depth was estimated relative to wheel diameter and other objects of known dimension. Water depth was inferred from the proportion of wheel

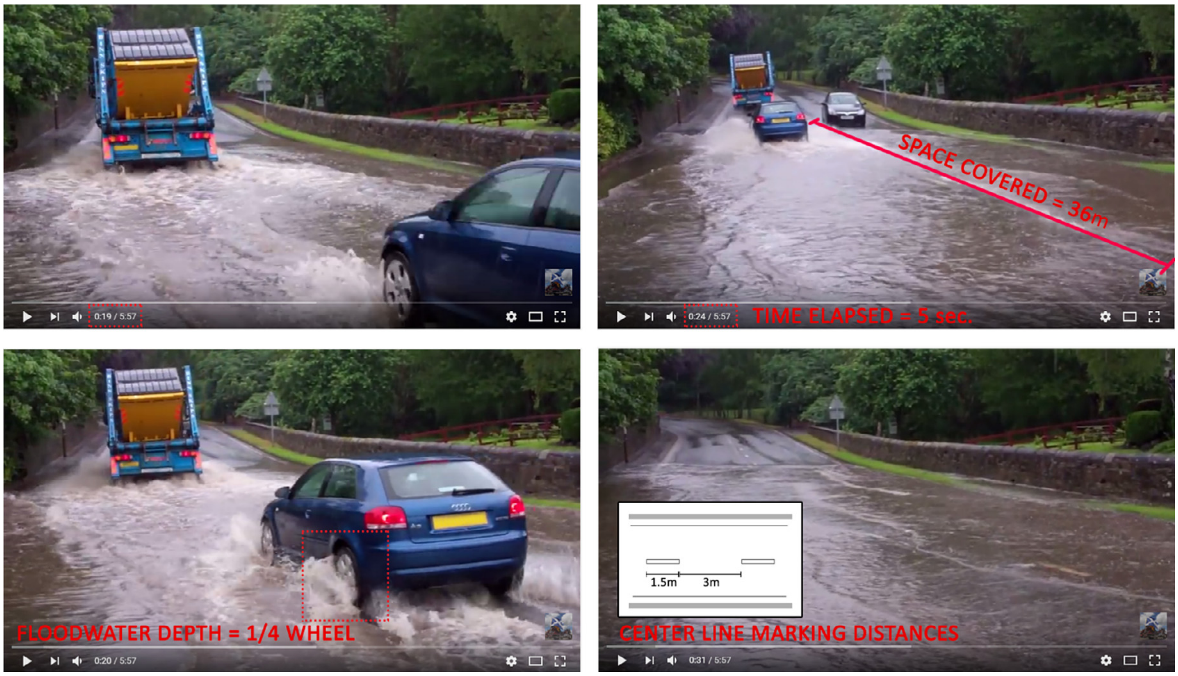


**Fig. 3.** Video screenshot for an Audi A3 driving through a flooded street in Perth (UK) in 2012.

that was submerged. Vehicle speed was estimated by analysing distance covered by the vehicle over a fixed time period by using road markings (if visible) or other objects of known dimension, as reference points. Fig. 3 gives an example of such procedure, on the basis of a video recorded in Perth (UK) in 2012, where $v_{car}$ [km/h] is calculated using:

$$v_{car} = 3.6 * \frac{d_{road\ signs}}{t_{elapsed}} \tag{5}$$

The nature of this calculation introduces a number of measurement uncertainties. For example, water perturbations around vehicle wheels make it harder to assess water depth, whilst inaccurate height and angle of the video lens introduce uncertainty into distance calculations. These errors are reflected by error bars in Fig. 2, but the results provide a complementary set of observations that compare well to other sources of data.

## 4. Pervasive and real-time observation to support flood disruption analysis

The depth-disruption function has been developed using best available data from the scientific and safety literature. However, increasingly local and national transport authorities are collecting data on through Automatic Traffic Counters (ATCs), CCTV, and other 'smart' transport sensors. Data from two traffic counters (see Fig. 1 for locations) in Newcastle upon Tyne from the 28th June 2012 flood are compared against baseline traffic flows in Fig. 4.

Nine Automatic Traffic Counters were active and providing useable data within the Newcastle City Council boundary (an area of 114 $km^2$). Undoubtedly the data in Fig. 4 show a marked impact of the flood event on traffic flow, as compared to average flow on Thursdays over the previous 3 years. However, only 60% of all Thursdays could be used. A proportion fell inside school holiday which have very different diurnal traffic patterns, whilst other days were affected by roadworks, public holidays, major sporting events, or a sensor failure. Moreover, the data confirms that despite the magnitude of the flood event the traffic continued to move highlighting the need for a more sophisticated approach to considering the disruptive impacts of flooding.

Fig. 5 plots the difference between baseline flows and traffic flow during the flood event, and also shows the time-series of rainfall intensity.

The event started at 3 pm, with intensity peaking 30 min later. The total rainfall within 2 hours was approximately equal to the average monthly rainfall. Interestingly, traffic volume shows a distinct increase of almost 300 vehicles per hour prior to, and peaking at the start of, the storm period. This storm was tracking from West to East across Great Britain and had already led to flooding elsewhere, and so this rise probably reflects those people who received and were able to act upon the weather forecast. An hour after the event started, just as the evening rush hour for commuters was beginning, traffic flows decreased rapidly relative to the baseline as storm drains filled and rainfall pooled on the roads. As the accumulated surface water began to drain away traffic flow increased relative to the baseline as traffic started flowing smoothly, and people who had not tried to return home earlier took to the road.

Unfortunately, this information is insufficient to inform the development of an improved depth-disruption function. The depth on the roads where the observations are made is not recorded, although this can be inferred from simulation models or derived from a photo, such as those in Fig. 1, if one is available. More significant is that the sensors only provide a count of vehicles, which does not include information on speed. Whilst speed reduction might be inferred from a comparison of the vehicle count data, it is unsound to attribute this to local flooding. The difference may also be due to blockage of a feeder road

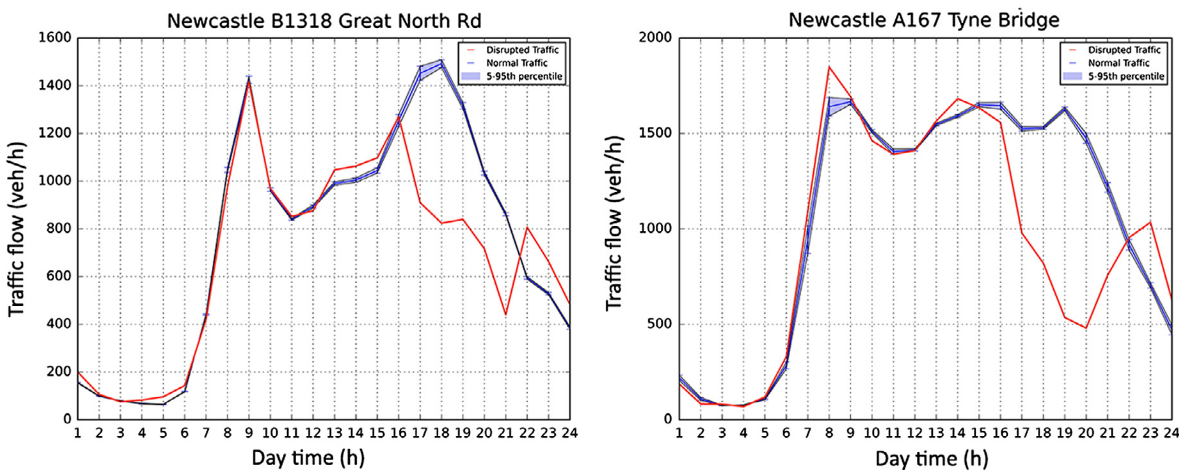


**Fig. 4.** Comparison of traffic flow at two locations (measured in cars counted by each sensor per hour) on Thursday 28th June 2012 with a baseline established by the 5–95th percentiles of traffic observations from all Thursdays outside of school holidays from the preceding 3 years.

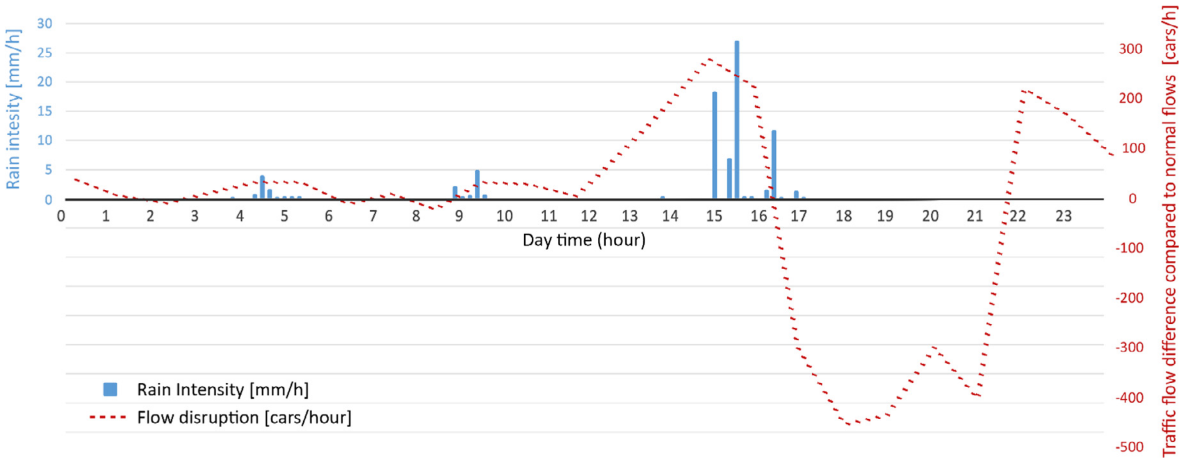


**Fig. 5.** An example of rainfall record from the weather station on the Great North Road, plotted together with the variation of the traffic flow during the 28th June 2012.

resulting in less traffic passing the counter, or slow moving traffic due to blockages and congestion on ensuing roads. However, routine collection of information on flood depth, vehicle speed and vehicle numbers at a high density across the city could be used in the depth-disruption function. Care would still be required to account for disruptions from other parts of the road network, but these could be accounted for by modelling the system to attribute local and network-wide effects. Increasingly pervasive sensing technologies, data from other sources including geotagged social media posts, coupled with big data analytics, offer the potential to monitor and observe the disruptive effects of flooding across numerous cities and the wider road network thereby providing a vast empirical dataset to progressively refine the function or construct a set of functions according to vehicle and road type.

## 5. Conclusions

Recognition of the significant economic impacts of disruption, and the threat to human safety, the assessment of impact of severe weather events on transport sector has attracted increased interest. Expected changes in climatic conditions, including increased frequency and intensity of precipitation will compound this challenge. Existing approaches to assess the disruptive impact of flooding on road transport are inadequate and fail to capture the dynamics and complex interactions between floodwater and the transport system, since typically a road is considered either fully operational or fully blocked which is not supported by observations. When financial resources for flood risk management are limited it is crucial to understand the impacts of flooding to prioritise investment decisions with the most informed analysis (Pregnolato et al., 2016).

This paper has reviewed observational, experimental, and modelling studies of the impacts of weather on transport. A significant subset of these papers have been used to derive an empirical function that, to the knowledge of the authors, for the first time relates the depth of floodwater on a road to vehicle speed. The depth-disruption function is complementary to the approach used by other flood impact functions in relating the magnitude of the impact to the flood loading. The maximum threshold for safe driving, stopping, and steering (without loss of control) is identified as 30 cm, on the basis of observations and driving tests; therefore, a road is assumed to be impassable only when the limit of 30 cm is reached. Incorporated into a standard flood risk analysis or transport appraisal calculation, this function can be used to calculate the disruption, measured in cost or time, expected from flooding. The function can also be used to raise driver awareness about safe driving depths.

The curve is the first attempt of flood-transport function and, as such, limited by a range of assumptions, which include the consideration of flood depth only as intensity measure. A future challenge is to consider not only vehicles in motion, but also the influence of flood velocities and associated debris on disruption. Expansion of the work could include consideration of other vehicle types (*e.g.* lorries) or modes of transport (*e.g.* tram, rail). Future data collection and further studies could refine this function and improve its applicability. Nevertheless, the curve developed by this study offers a necessary contribution, to move forwards from the binary consideration of flood roads on which existing transport models are based.

Full and reduced scale experiments have provided useful data to understand vehicle stability under parked conditions. Simulating moving vehicles is a natural progression from this work, although to cover the widest range of conditions and uncertainties would prove costly. Increased monitoring of transport systems offers the potential to improve this function by incorporating a richer set of observations. However, typical transport monitoring networks have not been established with this in purpose mind, and will need to be denser and record more than just the number of vehicles per unit of time, although other data sources may provide useful proxies.

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Data supporting this publication is openly available under an 'Open Data Commons Open Database License'. Additional metadata are available at: http://dx.doi.org/10.17634/121736-4. Please contact Newcastle Research Data Service at rdm@ncl.ac.uk for access instructions.

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