Road Congestion and Incident Duration

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Abstract

Non-recurrent congestion is frequently caused by accidents and other incidents. We estimate the causal effect of incident duration on drivers' time losses through changes in non-recurrent road congestion on Dutch highways. We demonstrate that incident duration has a strong positive, but concave, effect on non-recurrent congestion. The duration elasticity of non-recurrent congestion is about 0.40 implying that a one minute duration reduction generates a €60 gain per incident. We also show that at locations with high levels of recurrent congestion, non-recurrent congestion levels are considerably higher. At very congested locations, the benefit of reducing the incident duration by one minute is about €500 per incident. Public policies that prioritize duration reductions at congested locations are therefore more beneficial.

Keywords: congestion, vehicle-loss-hours, incident duration, accidents

1. Introduction

Traffic congestion is an omnipresent phenomenon during rush hour in densely-populated regions (see, for example, Arnott and Small, 1994; Downs, 2004). We focus on non-recurrent congestion on highways, which is mostly caused by road accidents, and other types of incidents (e.g., object on road, car breakdown).[1] This type of congestion constitutes roughly one-quarter of highway congestion (e.g., Snelder and Drolenga, 2011). In the current paper, we aim to estimate to what extent the level of non-recurrent congestion may be changed by public incident management policies and in particular by reducing the incident duration, i.e. the time it takes that all incident-associated traffic measures are lifted. Such measures include, for example, traffic warnings, speed reductions and lane closures. Lanes are seldom completely closed. For example, in the Netherlands, for 86% of incidents at least one lane is closed, but for only 8% of incidents all lanes are closed (Snelder and Drolenga, 2011). Given an incomplete closure of lanes, the time loss for a driver due to an incident is much shorter than the incident duration.[2] We assess the marginal costs of incident duration, distinguishing between the duration effects of accidents and other incidents.

Not only incident duration, but also traffic demand, and therefore recurrent congestion, determines non-recurrent congestion costs (for the literature on traffic demand and congestion, see, e.g., Beckmann et al., 1956; Goodwin, 2004; Small and Verhoef, 2007). The costs of non-recurrent congestion can be reduced through policies that shorten incident duration and re-establish traffic free flow.[3] The incident duration reduction effectiveness has been discussed widely, see for example, Carson et al. (1999). This connection between duration and non-recurrent congestion is also discussed in Garrison and Mannering (1990), who use a traffic simulation model for highways in the Seattle urban area. They find that it an extremely congested location where three out of four lanes are closed, $2,000 is lost in travel time for each additional minute of accident duration. Nam and Mannering (2000) show that the public agency that leads the responds to the incident (e.g., fire department or police) affects the length of the incident duration.[4]

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[1] We define an incident as an 'irregular' occurrence on a highway, including objects on the road, car break downs, one-sided or two-sided accidents.

[2] Our data, discussed later on, suggest that the time loss is only 18 to 25 % of incident duration.

[3] Incident duration studies often focus on the effects of incident characteristics on incident duration for specific highways, see, for example, Guiliano (1989) and Jones et al. (1991). These studies point out that incident duration depends on incident type and severity. We will see that the effect of incident duration almost fully captures the effects of incident characteristics on non-recurrent congestion.

[4] Lee and Fazio (2005) findings suggest that response time, i.e. the time it takes the incident manager to arrive at the location of an incident and clearance time, i.e. the crash-removing duration, are also a function of time and incident characteristics (e.g. severity, type of cars).

We contribute to the literature by estimating the effect of incident duration on non-recurrent congestion using microdata on incidents for the entire Dutch highway network. Importantly, in our estimation methodology, we take into account time-invariant, i.e. location, on a 100m precision level, as well as time-varying road characteristics, such as the level of recurrent congestion. Furthermore, we deal with selection effects and endogeneity issues. Our results show that there is a strong positive, but concave, effect of incident duration on non-recurrent congestion for accidents and other incidents.

2. Data and descriptives

Our data set comprises information on highway incidents from five types of road service providers (i.e., incident management organizations, towing companies, medical response teams, police and fire departments) for the years 2007 to 2009 for the entire Netherlands.[5] We also use traffic flow data from the Ministry of Infrastructure and the Environment (RWS), weather information of the Royal Netherlands Meteorological Institute (KNMI) and precipitation radar information (Buienradar).

In our analysis, the dependent variable is the level of non-recurrent congestion *as a result of an incident*. Most of the time, locations are incident free. However, at many locations traffic intensity may still regularly exceed road capacity and cause congestion. Hence, non-recurrent congestion is the *additional* increase of congestion due to an incident in comparison to the 'normal' situation - i.e. recurrent congestion level - at a certain location and time of the day. For each incident, we have accurate estimates for the levels of non-recurrent and recurrent congestion, based on traffic intensity and speed data obtained from induction loops. Congestion levels are calculated at the time and location of the incident for the entire highway network. Therefore, our congestion measure includes both primary congestion, i.e. on the lane(s) of the incident, and secondary congestion, i.e. on the opposite lane and spillback on the connections to other highways. Primary non-recurrent congestion accounts for about 70% of overall non-recurrent congestion [6]

Recurrent congestion is measured by the median weighted road congestion for each incident location and time of day, using an eight week window around the incident. To calculate the median, only observations within this window that are 'similar' to the time of the incident are included. To be precise, it includes the other six days of the week of the incident and the same day of the week for four weeks before and after the incident (congestion on the

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[5] Figure A1 in the Appendix shows a map of the national Dutch highway network. For a minor number of highways with low traffic intensity (north of Amsterdam and west of Breda), data is not available.
[6] The congestion measurement methodology is discussed in more detail by Snelder and Drolenga (2011).

day one week before and after the incident receives twice the weight).[7] Non-recurrent congestion is calculated as the difference between total congestion and recurrent congestion.[8] Congestion are measured in vehicle-loss-hours (VLH).[9] Incident duration is measured in minutes from the time when the incident is registered by RWS (the road service provider) until the time all traffic measures associated with the incident are lifted.

Table 1 – Descriptives of incident features

	Selected data set				Full data set
	(1) Positive recurrent congestion	(2) Positive recurrent congestion	(3) Positive recurrent congestion	(4) Zero recurrent congestion	(5)
	Accidents	Non-accidents			
Non-recurrent congestion (VLH)	449.6	367.1	424.9	61.1	62.1
Recurrent congestion (VLH)	103.9	94.2	101.0	0	22.6
Incident duration (minutes)	48.7	46.1	47.9	70.2	
Accident	1	0	0.70	0.61	0.39
Type of vehicle involved					
Passenger car	0.60	0.38	0.53	0.47	0.41
Truck	0.14	0.24	0.17	0.22	0.11
Motorcycle	0.019	0.0050	0.015	0.010	0.0053
Type of damage					
Injury and Fatality	0.10	0	0.073	0.079	0.014
Severe material damage	0.26	0	0.18	0.16	0.059
Number of observations	6,506	2,788	9,294	2,352	263,185

The full data set contains 263,185 incident observations of which about 40% are accidents, defined here incidents that involve a vehicle damage.[10] Registration of incident duration by the agencies involved (e.g., incident management crew, police) was not obligatory during the period of observation. For only 11,646 observations, the incident duration is known. We select these observations. Among these, recurrent congestion is zero for 2,352 observations (about 20% of the sample), but positive for 9,294 observations, see columns (3) and (4) in Table 1. We will focus on the latter group, because non-recurrent congestion levels are generally small when recurrent congestion is zero (see Table 1, (4)). So, a positive level of recurrent congestion is generally a condition that non-recurrent congestion occurs. The selected data set is clearly not random. For example, the shares of accidents and of incidents

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[7] For an example of how this median is calculated, see Table A1 in the Appendix.
[8] Non-recurrent congestion must be non-negative. However, due to limitations in the way recurrent congestion is approximated, non-recurrent congestion is negative in 0.02% of observations. We exclude these few observations.
[9] Hence, one car waiting in a traffic jam for one hour results in the same VLH as 60 cars delayed by one minute.
[10] We exclude observations when no information on type of incident (i.e., accident or no accident) is provided.

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with injuries and fatalities are larger in the selected data set (see Table 1).[11] Plausibly, incident managers devote more attention to these incidents, increasing the likelihood of recording incident duration. [12] In addition, the average levels of non-recurrent and recurrent congestion are five to six times larger in the selected data set, likely because locations and times with high traffic intensity are prioritized by road service providers.[13]

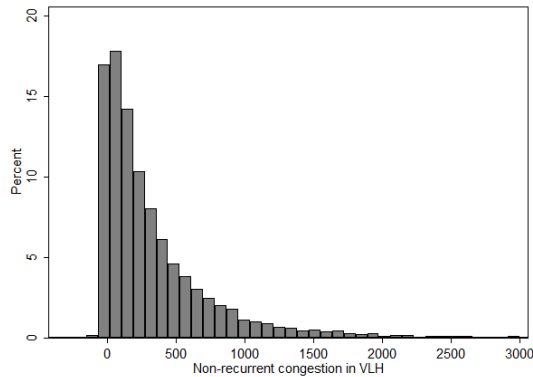**Figure 1 – Density of non-recurrent congestion**

Figure 3 – Density of incident duration
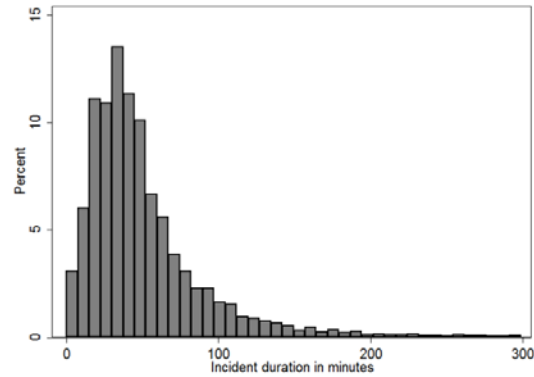
Figure 2- Density of recurrent congestion
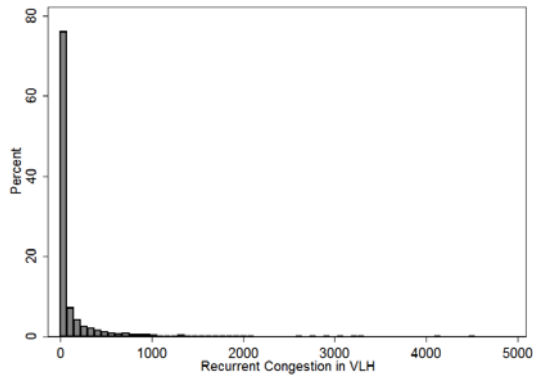
In the selected data set, accidents are similar to non-accidents in terms of average incident duration (46 and 49 minutes respectively) and recurrent congestion (94 and 104 VLH, respectively), but average levels of non-recurrent congestion are about 25% higher for accidents (450 and 361 VLH, respectively), see Table 1, (1) and (2). This table also shows that, by definition, incidents do not involve any damage or injuries, whereas about 36% of accidents involve fatalities, injuries or severe material damage.

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[11] For example, in the selected data set 68% of incidents are accidents whereas in the full data set it is 39%.
[12] Later on, we use a Heckman selection approach to deal with non-random data selection. The instrument used will depend on the source that reported the incident to RWS.
[13] For example, an incident (e.g., car break down) during the night on an empty highway will receive less attention from road service agencies than a fatal accident during rush hour on a congested highway.

Recurrent and non-recurrent congestion follow approximately an exponential distribution, so low values are more common than high values, see Figures 1 and 2. For example, the maximum of recurrent congestion in our data is 4,271 VLH which is 40 times larger than the average value of 101 VLH. In our data the variation in recurrent congestion between locations is much larger than the within variation over time. Hence, it is useful to label locations with larger levels of congestion as 'congested locations'. Accordingly, in the analysis of the incident duration effect later, we will distinguish between locations with average recurrent congestion and congested locations. Incident duration is approximately log-normal distributed (see Figure 3), and durations up to 100 minutes are particularly common. Figure 4 shows a positive, concave relationship between incident duration and non-recurrent congestion.[14] This positive effect is particularly clear for incident durations of less than 100 minutes (about 90% of observations).

Figure 4 - Non-recurrent congestion to incident duration
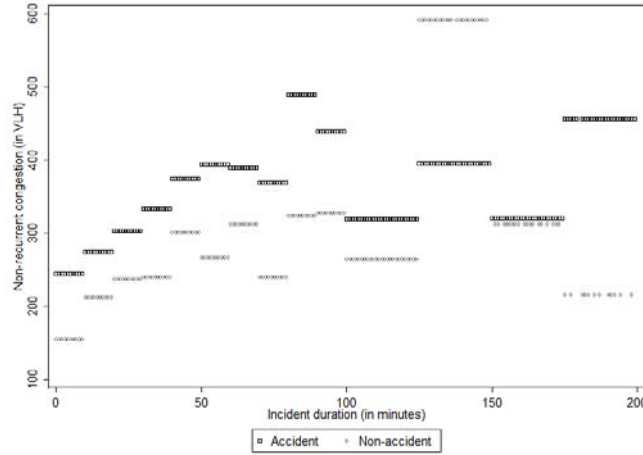
3. Method

To estimate the effect of incident duration on non-recurrent highway congestion, we estimate a log-linear specification for the 6,506 observations where recurrent congestion is positive.[15] Hence, we assume that the logarithm of non-recurrent congestion, $NRC_{i,t}$, at location i and time t, depends on the logarithm of recurrent congestion, $RC_{i,t}$, the logarithm of incident duration, $ID_{i,t}$, controls, $X_{i,t}$, location fixed effects, a_i, and an error term, $u_{i,t}$:

$$\log NRC_{i,t} = \beta \log RC_{i,t} + \gamma \log ID_{i,t} + \delta X_{i,t} + a_i + u_{i,t} . \qquad (1)$$

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[14] In this figure, incident duration is provided in intervals of 10 minutes for values below 100 minutes and in intervals of 25 minutes for values above 100 minutes. A few observations with durations that exceed 200 are excluded here.

[15] The logarithmic specification is most in line with the data. Later on, we also estimate a linear specification where we include locations with zero recurrent congestion (see, column 4 in Table 1).

We are particularly interested in the marginal effect of incident duration on non-recurrent congestion. Given the log-linear specification, the marginal effect of incident duration is:

$$\frac{\partial \text{NRC}_{i,t}}{\partial \text{ID}_{i,t}} = \gamma \, \frac{NRC_{i,t}}{ID_{i,t}} = \gamma \frac{RC_{i,t}{}^{\beta} z_{i,t}}{ID_{i,t}^{1-\gamma}}, \qquad\qquad (2)$$

where $z_{i,t} = \exp\left(\delta X_{i,t} + a_i + u_{i,t}\right)$. Because we will demonstrate that $\beta > 0$, this implies that the marginal benefit increases with the level of recurrent congestion, so there is a multiplicative effect of incident duration and recurrent congestion.

We estimate equation (1) separately for accidents and non-accidents to allow for the possibility of a difference in their determinants. We control for accident severity (e.g. fatality), car type involved (e.g. truck) and weather.[16] In addition, we include hour of the day, week(-end), month and year dummies and also include location fixed effects. For the main results, we use 100m location fixed effects for accidents and 1km location fixed effects for non-accidents (we use fewer location fixed effects for non-accidents because of fewer non-accidents observations, which allows for sufficient degrees of freedom to estimate the effects we are interested in).

One may argue that incident duration is endogenous because congestion may block road service providers and therefore increase incident duration. However, this argument does not apply in the Netherlands, because incident management crew and first-response vehicles have access to emergency lanes (and may approach incident location in opposite direction of the traffic), which allows them to travel unhindered.[17] Therefore, reverse causality is not a major concern.

We account for two other possible endogeneity problems: omitted variable bias and selection bias. First, heterogeneity in location, in terms of number of lanes, and proximity to on- and off-ramps may determine non-recurrent congestion. As stated above, we control for this unobserved heterogeneity in locations by using location fixed effects. Second, we account for data set selection bias with a Heckman correction two-step estimation approach (Heckman, 1979). In the selection equation, we use an instrument that directly affects the probability of incident duration being reported, but is unlikely to affect non-recurrent

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[16] Temperature and maximum wind gust in the past hour are recorded hourly at the national level (in a central location of the Netherlands). Precipitation is measured within 1km² of the incident location for intervals of 90 minutes (30 minutes before and 60 minutes after the incident registration). Furthermore, we construct a dummy for falling snow (the interaction of precipitation and temperature below zero degrees Celsius).

[17] They may also travel through the middle of two lanes as cars have opened up space as required by law.

congestion directly.[18] So, the source that reported the incident is used as an instrument that distinguishes between police, incident management personnel and other source. One technical difficulty is the large number of location fixed effects because this approach is non-linear and cannot be estimated with 4,553 fixed effects. For this reason, when using the Heckman correction approach we use 5km location dummies. The Heckman model results are very similar to the location fixed effects model that does not correct for selection effects. Hence, we focus on the latter.

Another issue is measurement error. Our construction of non-recurrent congestion is based on the measurement of recurrent congestion. It is likely that recurrent congestion has some measurement error (e.g., the median value is not representative for the true value of recurrent congestion). In this case, non-recurrent congestion, which is calculated using the difference between total and recurrent levels, will have measurement error which is negatively correlated to the measurement error of recurrent congestion. This implies that the effect of recurrent congestion might be negatively biased, so we likely somewhat underestimate the causal effect of recurrent congestion.

4. Estimation results

Table 2 shows the main results. For accidents, the incident duration elasticity of non-recurrent congestion is 0.43, see column (1). This estimate implies that an incident duration increase of one minute (about two percent of the mean duration) results on average in an increase in non-recurrent congestion of 3.95 VLH (0.86 percent of the mean recurrent congestion). Assuming a VLH monetary value of €20, which is in line with the literature, this implies that one minute of incident duration costs about €79.[19] For non-accidents, this elasticity is 0.32, see column (2), so about one-third lower than for accidents. Hence, one minute increase in non-accident duration leads to an increase of 2.34 VLH, equivalent to €47. Despite this difference, it appears that the elasticities of the accident and non-accident specification are not different at the 5% significance level (t=1.88). So, for our welfare calculations, we will not distinguish between the durations effects of accidents and non-accidents.[20] Similarly, the estimated

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[18] Hence, the source that reported the incident is assumed to be independent of non-recurrent congestion (conditional on controls), but the source affects the probability that the incident duration is reported in our data.
[19] There is a range of monetary values of travel time in the literature, see, for example, Calfee and Winston (1998) and Lam and Small (2001). Given an average occupancy of 1.6 persons per car, we implicitly use a value of time of €12.5 per person.
[20] Accidents are a small part of overall incidents but the main cause of non-recurrent congestion, according to Jones et al. (1991). In our case, because of the larger share of non-accidents and the similar elasticities, we arrive at the opposite conclusion.

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recurrent congestion elasticities for accidents and non-accidents are almost identical (0.25 and 0.30 respectively, $t = 1.93$).

Table 2 – Non-recurrent congestion

	(1) Accidents		(2) Non-accidents	
	Coefficient	Standard error	Coefficient	Standard error
Incident duration (log)	0.429 ***	0.039	0.317 ***	0.045
Recurrent congestion (log)	0.252 ***	0.016	0.303 ***	0.021
Injury and Fatality	0.055	0.095		
Material Damage (severe)	0.039	0.056		
Passenger car	0.101	0.063	-0.028	0.068
Truck	-0.033	0.063	-0.052	0.088
Motorcycle	0.216	0.183	0.270	0.343
Snow	-0.379	0.669	1.279 ***	0.469
Max. wind gust (in m/sec)	0.005	0.008	-0.009	0.010
Rain (in mm/hour) 0 to 2.5	0.098	0.070	0.262 ***	0.075
Above 2.5	-0.407	0.245	0.631 **	0.274
Temperature (in degree Celsius) 0 to 10	-0.161	0.147	-0.007	0.157
10 to 20	-0.115	0.167	0.169	0.189
Above 20	-0.265	0.190	0.177	0.219
Location-fixed-effects	100m		1km	
Year, month, hour and weekday of observation	Included		Included	
R^2 within	0.3327		0.2953	
R^2 overall	0.2808		0.2290	
Number of fixed-effects	4,553		1,139	
Number of observations	6,506		2,788	

Note: The logarithm of non-recurrent congestion is the dependent variable. ***, **,* imply 1, 5, 10% significance levels. Standard errors are robust.

Our results imply that there are substantial benefits of reducing incident duration. For example, a one-minute reduction of incident duration for all 135,000 annual highway incidents decreases non-recurrent congestion costs by €8.1 million.[21] The marginal benefit of one minute reduction is then, on average, €60.

We emphasize that we report the average value and the value strongly depends on the level of recurrent congestion, because of the multplicative effect with incident duration (see equation (2)), therefore, the benefit of a reduction at a location with a larger recurrent congestion is much larger. For example, in our data, the average level is 100 VLH. At

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[21] Because the incident duration elasticities of non-recurrent congestion for accidents and non-accidents are not statistically different, we use the weighted marginal average of 3.01 VLH (i.e. €60) for a one minute reduction.

locations with 2000 VLH of recurrent congestion, our estimates imply that non-recurrent congestion is, on average, 2.1 times higher than the given average levels of non-recurrent congestion, implying that the marginal benefit of reducing incident duration is 2.1 times higher (€126) than the average.[22] Therefore, Incident Management policies should prioritize locations according to recurrent congestion to minimize non-recurrent congestion costs.[23]

We re-estimate the model for a quadratic specification of incident duration (no logarithms). We do this for the data set that excludes and for the data set that includes recurrent congestion observations that are zero (the descriptives are reported in (1) and (3) of Table 1). For the former, the point estimate of incident duration of accidents equals 4.630 and the point estimate of its square is -0.004. For the latter, the point estimate equals 3.677 and the point estimate of its square is -0.003 (these coefficients are all significant at the 1% significance level). The marginal effects of accident duration are then 4.238 and 3.389 respectively (evaluated at the mean values). This translates to an accident duration elasticity of non-recurrent congestion of 0.47 and 0.38 respectively, which is similar to the results reported in Table 2. Therefore, this elasticity is robust over different specifications and data selections.

The estimated negative effect of the quadratic term of incident duration indicates that the effect on non-recurrent congestion is concave (consistent with Figure 4).[24] Therefore, the marginal effect is the highest just after the incident occurs and becomes less for longer durations. One possible reason for this concave effect is the effect of traffic information, rerouting and other incident management activities. For example, dissipation of traffic information about the incident-induced non-recurrent congestion to road participants may result in a decrease of inflow of cars. Other examples include, incident management personnel clearing the road, thereby restoring road capacity, better assessment of incident situation translating in better road management (i.e. speed reduction).[25] It might be that without (or with different) incident management policy and/or traffic information systems (i.e., in other countries), this effect is linear or even convex. For example, economic theory suggests that in a stylized case without rerouting and inelastic demand for travel, there is a quadratic effect of

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[22] Note that $(2000/100)^{0.252} = 2.1$.

[23] After 2009 this has been acknowledged by RWS (Immers et al., 2008), where incident management crews response times are required to be less for locations with high levels of recurrent congestion.

[24] We have also estimated models with a flexible dummy specification of incident duration. These models also show that the effect is concave.

[25] One can imagine that heavier incidents with longer durations trigger a stronger response from incident management crews reducing non-recurrent congestion. This interpretation is however conflicting with our result that incident characteristics and severity do not play a significant role in explaining non-recurrent congestion.

incident duration of non-recurrent congestion (Hall, 1993; Koster and Rietveld, 2011) suggesting that the elasticity would be 2 rather than values around 0.40 as reported by us.

We have noticed above that at more congested locations the benefit of a reduction in the incident duration is larger (as implied by the specification in logarithms). However, it is also plausible that the effects of logarithm recurrent congestion and logarithm incident duration interact. We address this issue for accidents. The results are reported in (1) of Table 3. We find a slight positive interaction effect but it is only significant at a 10% significance level.

Another way to address this issue is by excluding the large number of locations where recurrent congestion levels are low. Therefore, we re-estimate the model for accidents at locations with recurrent congestion above 5VLH (62% of our observations). The accident duration and recurrent congestion elasticities both increase by roughly 20%, as shown in column (2). This is consistent with the small positive interaction effect reported in column (1).

Table 3 – Non-recurrent congestion of accidents

	(1)			(2)			(3)		
	Interaction incident duration and recurrent congestion			Recurrent congestion > 5 VLH			Recurrent congestion > 100 VLH		
	Coefficient		Standard error	Coefficient		Standard error	Coefficient		Standard Error
Incident duration (log)	0.363	***	0.059	0.491	***	0.048	0.378	***	0.090
Incident duration (log)*recurrent congestion(log)	0.025	*	0.014						
Recurrent congestion (log)	0.160	***	0.053	0.325	***	0.030	0.575	***	0.092
Injury and Fatality	0.062		0.094	0.064		0.114	0.153		0.165
Material Damage (severe)	0.037		0.056	0.034		0.066	0.236	*	0.132
Passenger car	0.106	*	0.063	0.052		0.070	0.023		0.135
Truck	-0.033		0.092	-0.050		0.101	0.065		0.188
Motorcycle	0.209		0.183	-0.084		0.192	-0.465		0.269
Snow	-0.366		0.675	0.275		0.361	0.375		0.592
Max. wind gust (in m/sec)	0.005		0.008	-0.002		0.009	-0.002		0.017
Rain (in mm/hour) 0 to 2.5	0.101		0.070	0.123		0.077	0.010		0.132
Above 2.5	-0.408	*	0.244	0.253		0.221	0.048		0.250
Temperature (in degree Celsius) 0 to 10	-0.157		0.150	-0.188		0.181	0.008		0.223
10 to 20	-0.128		0.166	-0.169		0.203	-0.111		0.278
Above 20	-0.278		0.189	-0.369		0.234	-0.374		0.324
Location-fixed-effects	100m			100m			100m		
Year, month, hour and weekday of observation	Included			Included			Included		
R^2 within	0.3342			0.2686			0.3636		
R^2 overall	0.2836			0.1818			0.1339		
Number of fixed-effects	4,553			2,842			1,200		
Number of observations	6,506			3,992			1,499		

Note: In all three models, the logarithm of non-recurrent congestion is the dependent variable. ***, **,* imply 1, 5, 10% significance levels. All standard errors are robust.

Further evidence of this is provided in (3) of Table 3 where we restrict the data to congested locations with recurrent congestion above the average value of 100 VLH. The recurrent congestion elasticity doubles to 0.575, but the incident duration elasticity remains similar to the original estimate (see (1) of Table 2). Therefore, the incident duration elasticity is robust over different data set selections and over different model specifications, whereas the recurrent congestion elasticity is larger for congested locations. According to (3) in Table 3 at very congested locations (with 4000 VLH of recurrent congestion), the marginal effect of incident duration is 8.3 times larger than the marginal effect where the recurrent congestion is equal to the average, so a one minute duration costs about €500.[26] This reinforces our conclusion that Incident Management policies should prioritize those congested locations. Note that our estimate is low in comparison to the $2000 of Garrison and Mannering (1990) who also focus on congested locations but who consider a major urban highway with a severe incident that reduces capacity by 75% during rush hour. Our €500 refers to the *average* effect of incident duration for congested locations, irrespective of the numbers of lanes closed and irrespective of the hour of the day.

Non-recurrent congestion is not the only component of incident welfare losses. Another component is time loss due to rerouting. In case the incident duration is long and congestion levels are high, so expected time loss in the queue is long, it may be beneficial for drivers to make a detour that increases their travel time costs but reduces their time in the queue. [27] In our data, drivers' average delay in the queue is 18% to 25% of incident duration (because most of the time not all lanes are closed).[28] Hence, it is plausible that drivers make only a detour for very long incident durations (i.e. longer than an hour).

The additional costs of an incident vary with the number of road users who make a detour, which depends on the availability of route alternatives (e.g., a link to another highway) and information to the road user about the occurrence of the incident. According to the Wardrop (1952) principle, when drivers are well-informed, a certain proportion of drivers decide to make a detour so that in the end the travel time for those who stay in the queue and

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[26] Note that $(4000/100)^{0.575} = 8.3$.

[27] The average distance between two highways is 13.2km for the most frequented urban area (i.e. Randstad). In the Netherlands, highways have predominantly replaced the pre-existing provincial road network, so usually taking a detour on another highway is the only reasonable alternative. If road users choose the route alternative that minimizes (expected) travel time, the detour time has to be equal to or less than, the congestion delay. So only for very long incident duration drivers consider detours.

[28] This is calculated as follows. For incidents longer than one hour the non-recurrent congestion average is 880VLH. The drivers delay is then between 880/4800=18% (for a four-lane highway with 4,800 vehicles per hour) and 880/3600=25% (for a three-lane highway with 3,600 vehicles per hour) at congested locations.

those who make a detour is the same.[29] In the Netherlands, around 20% of road users choose to detour if they have been informed on a delay of one hour (Peer, 2013). The results by Emmerink et al. (1996) suggest a similar percentage. Assuming this percentage to be true, we may underestimate the total welfare loss (i.e. the sum of non-recurrent congestion and detour time costs) by up to 25% at very congested locations with long incident durations. So, on average, detour time cost adds much less than 25% to the overall welfare costs.[30] Note that in addition to rerouting there are other behavioural responses such as rescheduling of activities that imply welfare losses that are not included here.

Incident characteristics (e.g. injury, truck involved) are an explanatory factor of incident duration, as shown, for example by Guiliano (1989) and Nam and Mannering (2000).[31] When controlling for 100m location fixed effects and incident duration the effect of accident characteristics is insignificant. Therefore, incident duration is the important factor in explaining non-recurrent congestion and captures the effects of the other accident characteristics - vehicle type and severity.[32] Weather conditions do not seem to affect accident non-recurrent congestion, but precipitation increases non-recurrent congestion of non-accidents.[33]

5. Sensitivity Analyses

We conduct several sensitivity analyses of the results. We focus here on the accidents for which we have more observations. First, we increase the location-fixed-effects group variable to 1km (see Table 4, (1)) as well as to 5km (Table A2, (2) in the Appendix), and estimate models without controlling for location fixed effects (see Table 4, (2)).[34] The effects of incident duration and recurrent congestion are very similar in size with those discussed before. So, our main results are not sensitive to the inclusion of the definition of fixed effects.

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[29] Note that by making the detour, the latter reduce the waiting time of those who continue to wait in the queue.

[30] Of the 100% of drivers affected by an incident, 80% do not change route and 20% make a detour. Using the Wardrop principle, the travel time loss of the group that changes route is 20/80=25% of the group that does not change route. This would imply an extra welfare loss of 25%.

[31] We also estimated the effect of incident characteristics on non-recurrent congestion without including incident duration. The effects of many characteristics become then significant (results are not shown here). We also estimated models on incident duration as a function of incident characteristics, time of day, week, month, year and weather. These results are similar to those found in Vukovic et al. (2013).

[32] However, when using less location fixed effects or not controlling for fixed effects some of the accident characteristics become significant.

[33] For example, the presence of snow strongly increases non-recurrent congestion. The effect of snow and heavy rain between recurrent and non-recurrent congestion cannot be disentangled here because we do not observe the weather for recurrent congestion.

[34] The location precision level decrease may result in introducing unobserved heterogeneity bias. For example, a 1km road segment with an on- and off-ramp in front of the accident could change the resulting non-recurrent congestion because of the possibility of re-routing. Also, incident clearance, number of lanes, and other factors could be non-homogenous in space.

Second, for the Heckman correction model (see (1) of Table A2, in the Appendix), the elasticities of incident duration and recurrent congestion are almost identical to the results dicsussed above.[35]

Table 4 – Sensitivity Analysis- Non-recurrent congestion of accidents

	(1) 1km location			(2) No location control			(3) Recurrent congestion not included		
	Coefficient		Standard error	Coefficient		Standard error	Coefficient		Standard error
Incident duration (log)	0.406	***	0.028	0.370	***	0.027	0.447	***	0.043
Recurrent congestion (log)	0.236	***	0.113	0.204	***	0.007			
Injury and Fatality	0.161	***	0.059	0.150	***	0.058	0.011		0.102
Material Damage (severe)	0.109	***	0.037	0.115	***	0.037	0.067		0.060
Passenger car	0.090	**	0.043	0.239	***	0.042	0.115		0.071
Truck	0.065		0.061	0.102	*	0.057	-0.049		0.102
Motorcycle	0.255	**	0.111	0.202	*	0.118	0.360	*	0.199
Snow	-0.043		0.474	0.433		0.462	-0.512		0.707
Max. wind gust (in m/sec)	0.007		0.006	0.005		0.005	0.001		0.008
Rain (in mm/hour) 0 to 2.5	0.096	**	0.042	0.082	**	0.041	0.135	*	0.076
Above 2.5	-0.436	**	0.022	-0.399	*	0.217	-0.435		0.300
Temperature (in degree Celsius) 0 to 10	-0.434		0.104	0.018		0.104	-0.246		0.168
10 to 20	0.020		0.113	0.083		0.115	-0.189		0.190
Above 20	-0.119		0.126	0.014		0.129	-0.226		0.214
Location-fixed-effects	1km			Not included			100 meters		
Year, month, hour and weekday of observation	Included			Included			Included		
R² (within)	0.3217			0.3167			0.1915		
R² overall	0.3066						0.1397		
Number of fixed-effects	1,680						4,553		
Number of Observation	6,506			6,506			6,506		

Note: In all three models, the logarithm of non-recurrent congestion is the dependent variable. ***, **,* imply 1, 5, 10% significance levels. Standard errors are robust.

Third, we re-estimate the model not controlling for recurrent congestion. The results ((3) in Table 4) show that the incident duration elasticity estimate is then biased upwards. Therefore, controlling for recurrent congestion is important to obtain consistent estimates of efffect of incident duration on non-recurrent congestion.

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[35] It also appears that our instrument is highly statistically significant and has the expected effect on the probablitiy of reporting incident duration. We find that when the police is the source of reporting the duration is more likely to be reported. One possible explanation is that when the police reports the incident to the traffic control regional office, traffic measures (e.g., speed reduction) are more likely to be applied, which increases the probability that incident duration is observed and recorded. In contrast, when incident management crews are the first to report the incident, the duration might not be recorded because the crew is busy dealing with the incident and does not request traffic measures.

6. Conclusion

Our estimates show that incident duration substantially increases the level of non-recurrent congestion on highways. The incident duration elasticity of non-recurrent congestion is about 0.40 and similar for accidents and non-accidents. This implies that one marginal minute incident duration costs about €60 per incident. The annual economic value of one marginal minute incident duration reduction is then €8.1 million for the Netherlands. In addition, we show that the marginal effect of incident duration on non-recurring congestion is diminishing. Therefore, incident management policies should focus on reducing all durations, not in particular the longer ones.

Furthermore, recurrent congestion has a strong positive effect on non-recurrent congestion. Recurrent congestion and incident duration have a multiplicative effect on non-recurrent congestion. This implies that incident management policy should focus on locations with larger recurrent congestion levels, because there the reduction in incident duration has a larger impact. For very congested locations the marginal cost of one minute duration is about €500 per incident. Including other aspects of incident management policies in the future research, such as the type of road measures applied, may increase our understanding of the effect of incident management on welfare.

Appendix

Figure A1- National Dutch highway network
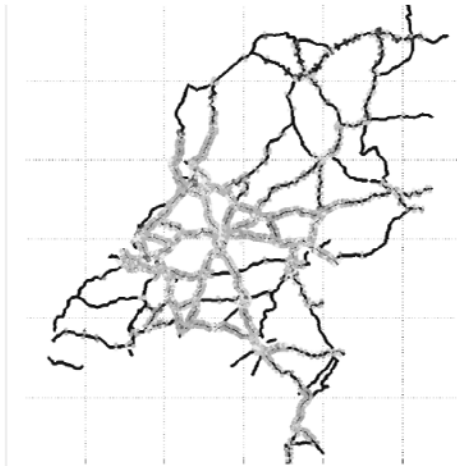
Source: Vukovic et. al., 2013

Table A1 - Recurrent congestion matrix

	Time in Weeks								
	-4	-3	-2	-1		+1	+2	+3	+4
Weekdays					Monday Tuesday Wednesday Thursday				
	Friday	Friday	Friday	Friday weighted	Friday (F)	Friday weighted	Friday	Friday	Friday
					Saturday Sunday				

Note: Here, the incident is on a Friday (in grey). Recurrent congestion values of the Friday one week before and after the incident receive a weight of two.

Table A2 – Heckman selection model for logarithm of accident non-recurrent congestion

		(1) Heckman		(2) Standard	
		Coefficient	Standard error	Coefficient	Standard error
Logarithm non-recurrent congestion	Incident duration (log)	0.388 ***	0.023	0.388 ***	0.024
	Recurrent congestion (log)	0.228 ***	0.011	0.221 ***	0.006
	Injury and Fatality	0.281	0.200	0.157 **	0.055
	Material Damage (severe)	0.200	0.124	0.124 **	0.037
	Passenger car	0.230 **	0.071	0.191 ***	0.039
	Truck	0.192 **	0.097	0.139 **	0.055
	Motorcycle	0.265 *	0.148	0.206 **	0.120
	Snow	0.155	0.295	0.086 **	0.041
	Max. wind gust (in m/sec)	0.005	0.005	0.005	0.001
	Rain (in mm/hour) 0 to 2.5	0.101 **	0.041	0.086 **	0.041
	Above 2.5	-0.492	0.171	0.005	0.005
	Temperature (in degree Celsius) 0 to 10	0.029	0.095	0.030	0.096
	10 to 20	0.118	0.105	0.108	0.107
	Above 20	0.038	0.120	0.041	0.121
	Location-fixed-effects	5km		5km	
	Year, month, hour and weekday of observation	Included		Included	
Selection - incident duration reported	Recurrent congestion (log)	0.047 ***	0.003		
	Injury and Fatality	0.930 ***	0.035		
	Material Damage (severe)	0.546 ***	0.021		
	Passenger car	0.254 ***	0.029		
	Truck	0.378 ***	0.029		
	Motorcycle	0.436 ***	0.074		
	Snow	-0.381	0.135		
	Max. wind gust (in m/sec)	0.002	0.003		
	Rain (in mm/hour) 0 to 2.5	-0.059 ***	0.021		
	Above 2.5	-0.210 **	0.083		
	Temperature (in degree Celsius) 0 to 10	0.052	0.050		
	10 to 20	0.081 **	0.056		
	Above 20	0.120 **	0.064		
	Report police (instrument)	**0.084 *** **	**0.024**		
	Report Incident Management (instrument)	**-0.206 *** **	**0.037**		
	Location-fixed-effects	5km			
	Year, month, hour and weekday of observation	Included			
	Sigma	1.200			
	Rho	0.156			
	Lambda	0.188	0.293		
	Number of observations	34,524		6,506	

Note: In both models the logarithm of non-recurrent congestion is the dependent variable. Standard errors are robust. ***, **,* imply 1, 5, 10% significance levels.

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