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Fatal crashes involving large numbers of vehicles and weather

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ABSTRACT

Introduction: Adverse weather has been recognized as a significant threat to traffic safety. However, relationships between fatal crashes involving large numbers of vehicles and weather are rarely studied according to the low occurrence of crashes involving large numbers of vehicles. *Method:* By using all 1,513,792 fatal crashes in the Fatality Analysis Reporting System (FARS) data, 1975–2014, we successfully described these relationships. *Results:* We found: (a) fatal crashes involving more than 35 vehicles are most likely to occur in snow or fog; (b) fatal crashes in rain are three times as likely to involve 10 or more vehicles as fatal crashes in good weather; (c) fatal crashes in snow [or fog] are 24 times [35 times] as likely to involve 10 or more vehicles as fatal crashes in good weather. If the example had used 20 vehicles, the risk ratios would be 6 for rain, 158 for snow, and 171 for fog. *Conclusions:* To reduce the risk of involvement in fatal crashes with large numbers of vehicles, drivers should slow down more than they currently do under adverse weather conditions. Driver deaths per fatal crash increase slowly with increasing numbers of involved vehicles when it is snowing or raining, but more steeply when clear or foggy. *Practical applications:* We conclude that in order to reduce risk of involvement in crashes involving large numbers of vehicles, drivers must reduce speed in fog, and in snow or rain, reduce speed by even more than they already do.

1. Introduction

All 1,513,792 fatal crashes documented in the Fatality Analysis Reporting System [FARS] (NHTSA, 2016) are used to examine how weather affects fatal crashes involving large numbers of vehicles. Such crashes provide robust empirical evidence that is interpreted to provide information on how weather more generally affects risk of fatal crashes.

Nearly all (94%) fatal crashes in the United States involve, at most, two vehicles, so fatal crashes involving large numbers of vehicles are rare. There are eight crashes per year involving 10 or more vehicles, fewer than one involving 27 or more vehicles.

In order to obtain enough cases for analysis, we accumulated data over the entire period for which FARS data are available, namely, the 40 years 1975 thru 2014. The accumulated more than 1.5 million fatal crashes allow us to explore how weather affects the occurrence of fatal crashes as a function of the number of involved vehicles and to explore what happens when that number becomes large.

The rare crashes studied here are not a major component of the overall harm caused by 30,000 annual U.S. fatal crashes. However, they cause numbers of deaths that would be considered an important national public health problem in any context other than traffic. Over the study period, more than a thousand people were killed in crashes involving eight or more vehicles. This provides sufficient reason to encourage their study. Additionally, the analyses presented here show that fatal crashes involving many vehicles can solidify understanding of the role of weather in fatal crashes in general, and encourage countermeasures.

There is an extensive literature on weather effects on traffic safety. The investigation most similar in data source to the present is that of Eisenberg and Warner (2005), who used 1975–2000 FARS and other data to investigate effects of snowfalls on crashes, injuries, and fatalities. Many methods and approaches have been deployed to investigate relationships between weather and traffic safety. These include using crash data (Moore & Cooper, 1972; Orne & Yang, 1972; Codling, 1971; Satterthwaite, 1976; Evans, 1991), driving simulators (e.g. Saffarian, Happee, & Winter, 2012), questionnaires (Hassan & Abdel-Aty, 2011), behavioral investigations (Kilpeläinen & Summala, 2007), literature reviews (Theofilatos & Yannis, 2014), and case studies (e.g., Chakrabarty & Gupta, 2013). Many reported effects compliment the present investigation, as discussed later. We believe the present study is the first to empirically investigate relationships between crashes involving large numbers of vehicles and weather.

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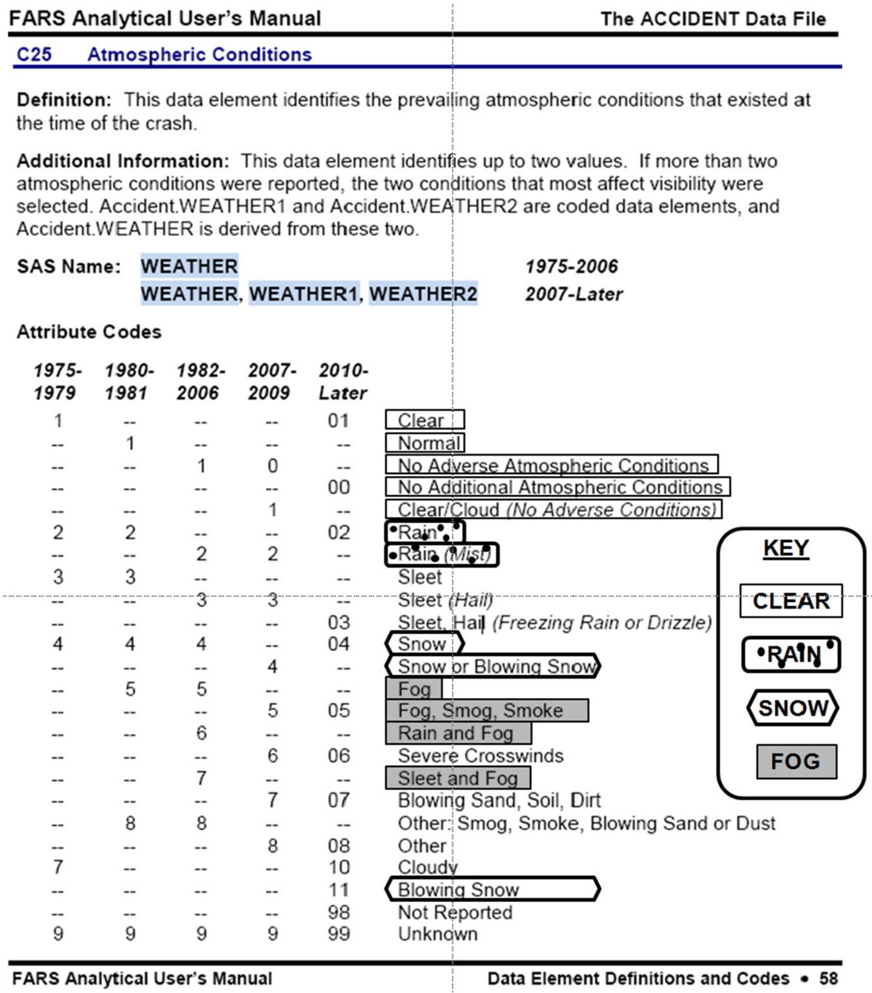

FARS Analytical User's Manual — The ACCIDENT Data File

C25 Atmospheric Conditions

Definition: This data element identifies the prevailing atmospheric conditions that existed at the time of the crash.

Additional Information: This data element identifies up to two values. If more than two atmospheric conditions were reported, the two conditions that most affect visibility were selected. Accident.WEATHER1 and Accident.WEATHER2 are coded data elements, and Accident.WEATHER is derived from these two.

SAS Name: WEATHER *1975-2006*
WEATHER, WEATHER1, WEATHER2 *2007-Later*

Attribute Codes

1975-1979	1980-1981	1982-2006	2007-2009	2010-Later	
1	--	--	--	01	Clear
--	1	--	--	--	Normal
--	--	1	0	--	No Adverse Atmospheric Conditions
--	--	--	--	00	No Additional Atmospheric Conditions
--	--	--	1	--	Clear/Cloud *(No Adverse Conditions)*
2	2	--	--	02	Rain
--	--	2	2	--	Rain *(Mist)*
3	3	--	--	--	Sleet
--	--	3	3	--	Sleet *(Hail)*
--	--	--	--	03	Sleet, Hail *(Freezing Rain or Drizzle)*
4	4	4	--	04	Snow
--	--	--	4	--	Snow or Blowing Snow
--	5	5	--	--	Fog
--	--	--	5	05	Fog, Smog, Smoke
--	--	6	--	--	Rain and Fog
--	--	--	6	06	Severe Crosswinds
--	--	7	--	--	Sleet and Fog
--	--	--	7	07	Blowing Sand, Soil, Dirt
--	8	8	--	--	Other: Smog, Smoke, Blowing Sand or Dust
--	--	--	8	08	Other
7	--	--	--	10	Cloudy
--	--	--	--	11	Blowing Snow
--	--	--	--	98	Not Reported
9	9	9	9	99	Unknown

FARS Analytical User's Manual — Data Element Definitions and Codes • 58

Fig. 1. Annotated copy of page 58 of *FARS Analytical User's Manual (1975–2011)* (NHTSA, 2013). Note: The weather categories CLEAR, RAIN, SNOW, FOG, and XTRA included all data, with XTRA including all 10 rows of data not assigned to the specific 4 weather categories.

2. Data and methods

The atmospheric, or weather, conditions used in FARS are shown in Fig. 1, reproduced from the *FARS Analytical User's Manual (1975–2011)* (NHTSA, 2013) The reasons for such a complex structure is that over the years increasing experience and enormously increased computer storage facilitated ongoing refinements. We focus on four weather conditions, CLEAR, RAIN, SNOW, and FOG, extracted from the items in Fig. 1 and accumulate data from the 40 years, 1975 through 2014. An additional condition, XTRA, includes the 10 items that do not fit into any of the 4 weather conditions. This additional category (which will not be mentioned again) facilitated the many checks that were performed at every stage of the analysis to ensure that all tabulations were correct.

Table 1
Distribution of the 1,513,792 fatal crashes leading to 1,002,359 driver deaths.
Source: FARS, 1975–2014.

Weather	Fatal crashes	Percent	Driver deaths	Percent
CLEAR	1,298,855	85.80	858,526	85.65
RAIN	127,328	8.41	83,335	8.31
SNOW	24,695	1.63	16,860	1.68
FOG	22,745	1.50	16,530	1.65
XTRA	40,169	2.65	27,108	2.70
Total	1,513,792	100.00	1,002,359	100.00

The study investigates the weather conditions at the time of the crash. That is, conditions that affect visibility. For example, SNOW means that snow is falling at the time of the crash; crashes with snow on the roadway surface are not included in the SNOW category unless it is snowing.

The distribution of the fatal crashes into the weather conditions is shown in Table 1. Also shown is the distribution for the 1,002,359 drivers killed in these crashes. We focus on driver deaths rather than total fatalities because every involved vehicle has one driver at risk, whereas a vehicle with many occupants has the potential to produce many deaths from a single vehicle. Inferences based on driver deaths are more directly related to crash risk (Evans, 2004).

These same data according to the number of vehicles, n, involved in the fatal crash are shown in Table 2. We use $t_{RAIN}(n)$ to denote the number of fatal crashes involving n vehicles that occurred in rain, and $d_{RAIN}(n)$ to denote the number of drivers killed in these crashes, with corresponding definitions for the other atmospheric conditions. Note that for $n = 41$ and $n = 90$ there are no driver deaths. These crashes are included because for each there is one fatal crash, but the driver was not killed. Table 1 implies that there were $1{,}513{,}792 - 1{,}002{,}359 = 511{,}433$ fatal crashes in which no drivers were killed. We chose to include all crashes to increase sample sizes and to avoid the complexity of having to specify an essentially arbitrary list of exclusion criteria. All quantities in this paper can be derived from the data in Table 2.

Table 2
Numbers of fatal crashes and driver fatalities versus the number of involved vehicles. Source: FARS 1975–2014.

n	Numbers of fatal crashes				Numbers of driver deaths			
	t_{CLEAR}	t_{RAIN}	t_{SNOW}	t_{FOG}	d_{CLEAR}	d_{RAIN}	d_{SNOW}	d_{FOG}
1	776,756	66,711	10,228	13,042	435,114	35,907	6,135	8,220
2	451,557	50,879	12,502	8,112	365,633	39,759	9,292	6,929
3	55,855	7,634	1,506	1,106	45,357	5,995	1,091	906
4	10,351	1,539	269	214	8,567	1,215	195	184
5	2,790	336	82	95	2,391	268	55	83
6	850	111	26	44	742	93	24	42
7	364	47	11	28	356	41	6	29
8	141	19	11	19	141	12	6	21
9	79	17	10	14	81	14	7	18
10	34	11	4	14	35	10	1	19
11	23	3	3	12	37	2	3	15
12	18	2	3	4	20	2	2	5
13	10	3	1	4	9	1	1	2
14	5	1	3	3	8	1	1	4
15	5	3	5	2	7	3	4	1
16	6	2	2	4	7	1	1	6
17		1	3	1		2	1	
18	2	2	1	2	3	2	1	2
19	1	2	1	1		1	1	1
20	1		2	1	4		2	2
21	1			1				1
22	2	1	4	3	3	1	4	2
23		2	2	1		2	1	2
24				4				13
26			1	1			1	1
27	1				1			
28			1	1				2
29			1	1			1	
30				1				1
31	1		1		1		1	
32		1	1	1		1	6	1
34		1				2		
35			1				1	
36	1		1				1	
37				1				4
38			1	1			2	1
40			1				2	
41				1				
42			1	1			4	
43				1				1
45			1	1			1	
47			1				1	
50				1				9
51			1				1	
56			1				3	
57			1				1	
58				1				2
80	1				9			
90			1					
92				1				1

n is number of involved vehicles. Missing values such as $n = 25$ mean that there were no fatal crashes involving 25 vehicles. Zeros are left blank for enhanced readability.

3. Results

3.1. Weather effects on number of vehicles involved in fatal crashes

An immediate observation from Table 2 is that the atmospheric conditions producing fatal crashes with the largest numbers of vehicles are FOG and SNOW, this even despite the overwhelming prevalence of CLEAR crashes documented in Table 1. The largest number of vehicles involved in any fatal crash was a 92-vehicle crash that occurred in FOG. The second largest was a 90-vehicle crash that occurred in SNOW. No fatal crashes involving 35 or more vehicles occurred in RAIN, compared to 11 in SNOW, 9 in FOG (and 2 when CLEAR).

This example shows the need to focus not on the number of fatal crashes involving a specific number of vehicles, but rather the number involving n or more vehicles, which we represent by N. We introduce $T(N)$ to represent the number of fatal crashes involving N or more vehicles, given by the values accumulated from the bottom in Table 2. Formally,

$$T_{CLEAR}(N) = \sum_{i=n}^{\infty} t_{CLEAR}(i) \tag{1}$$

with corresponding equations for the other atmospheric conditions, and corresponding equations applying to driver deaths with t and T replaced by d and D. The sum here ends at $n = 92$, not ∞.

Using n or more vehicles rather than n increases sample sizes and ensures that the sparse data for fatal crashes involving very large numbers of vehicles that could not be analyzed in isolation still contribute. For RAIN, between $n = 92$ and $n = 24$, there are only two non-zero entries, each for one fatal crash. Hence $T_{RAIN}(24) = 2$ is the number of fatal crashes involving 24 or more vehicles. Such a small sample size is unsuitable for much analysis. So Table 3 shows only $N \le 23$ values, although the figures will still include the larger values.

The value $T(1)$ gives the number of fatal crashes with one or more vehicles. This is identical to the number of crashes documented in FARS. The values of $T(1)$ are accordingly identical to those in Table 1.

Fig. 2 shows how $T(N)$ depends on N. A logarithmic scale is used because of the wide variation.

The raw numbers in Fig. 2 do not take account of the highly non-uniform distribution of the atmospheric conditions shown in Table 1. We accordingly introduce a measure, $\boldsymbol{\rho}$, that effectively normalizes for the prevalence of the different weather conditions. This is defined as.

$$\boldsymbol{\rho}_{CLEAR}(N) = T_{CLEAR)}(N)/T_{CLEAR)}(1) \tag{2}$$

with corresponding definitions for the other atmospheric conditions. So $\boldsymbol{\rho}_{CLEAR}(N)$ gives the probability that a CLEAR crash with N or more vehicles occurs compared to the probability that any CLEAR crash occurs.

The values of $\boldsymbol{\rho}$ listed in Table 3 show $\boldsymbol{\rho}_{SNOW}(2) = 0.5858$. That is, 59% of fatal SNOW crashes are multivehicle (involve 2 or more vehicles). We see immediately important differences. The corresponding value for CLEAR is much lower at 40%. Values for RAIN and FOG are also lower at 48% and 43%. Because $\boldsymbol{\rho}$ decreases rapidly to small values with increasing N, it is shown plotted in Fig. 3 on a log scale.

3.2. Comparison of relative risks under different weather conditions

Taking as an example $N = 6$, we observe that $\boldsymbol{\rho}_{FOG}(6) = 0.00774$ and $\boldsymbol{\rho}_{CLEAR}(6) = 0.00119$. That is, in fog, given that a fatal crash occurs, it is 6.5 times as likely to involve 6 or more vehicles compared to the corresponding situation in clear weather.

To examine more generally, let us introduce.

$$R_i = \boldsymbol{\rho}_i / \boldsymbol{\rho}_{CLEAR} \tag{3}$$

where i assumes the values RAIN, SNOW, or FOG. Table 3 includes R_i, which is plotted in Fig. 4.

The interpretation is that, given you are in a fatal crash, the probability it will involve 10 or more vehicles is three times as great if it is raining than if it is clear [$R_{RAIN}(10) = 3.19$ in Table 3]. Comparisons for the other two atmospheric conditions produce even more dramatic differences [$R_{SNOW}(10) = 23$ and $R_{FOG}(10) = 36$]. These already large differences, larger than those normally encountered in traffic safety (Evans, 2004), increase to even larger values as N increases (Fig. 4).

These comparisons show that given that a vehicle is involved in a fatal crash, the probability that it is multivehicle is larger for all the adverse environmental conditions than when weather is clear. Given that a vehicle is involved in a fatal crash, the probability that the crash involves a specified number of vehicles increases faster as the number of involved vehicles increases for all the adverse atmospheric than for

Table 3
Derivations from the raw numbers in Table 2.

N	T_{CLEAR}	T_{RAIN}	T_{SNOW}	T_{FOG}	ρ_{CLEAR}	ρ_{RAIN}	ρ_{SNOW}	ρ_{FOG}	R_{RAIN}	R_{SNOW}	R_{FOG}
1	1,298,855	127,328	24,695	22,745	1.0000	1.0000	1.0000	1.0000	1.00	1.00	1.00
2	522,099	60,617	14,467	9,703	0.4020	0.4761	0.5858	0.4266	1.18	1.46	1.06
3	70,542	9,738	1,965	1,591	0.0543	0.0765	0.0796	0.0699	1.41	1.47	1.29
4	14,687	2,104	459	485	0.0113	0.0165	0.0186	0.0213	1.46	1.64	1.89
5	4,336	565	190	271	0.0033	0.0044	0.0077	0.0119	1.33	2.30	3.57
6	1,546	229	108	176	0.0012	0.0018	0.0044	0.0077	1.51	3.67	6.50
7	696	118	82	132	5.4E−04	9.3E−04	0.0033	0.0058	1.73	6.20	10.83
8	332	71	71	104	2.6E−04	5.6E−04	0.0029	0.0046	2.18	11.25	17.89
9	191	52	60	85	1.5E−04	4.1E−04	0.0024	0.0037	2.78	16.52	25.41
10	112	35	50	71	8.6E−05	2.7E−04	0.0020	0.0031	3.19	23.48	36.20
11	78	24	46	57	6.0E−05	1.9E−04	0.0019	0.0025	3.14	31.02	41.73
12	55	21	43	45	4.2E−05	1.6E−04	0.0017	0.0020	3.89	41.12	46.72
13	37	19	40	41	2.8E−05	1.5E−04	0.0016	0.0018	5.24	56.86	63.28
14	27	16	39	37	2.1E−05	1.3E−04	0.0016	0.0016	6.04	75.97	78.26
15	22	15	36	34	1.7E−05	1.2E−04	0.0015	0.0015	6.96	86.07	88.25
16	17	12	31	32	1.3E−05	9.4E−05	0.0013	0.0014	7.20	95.91	107.49
17	11	10	29	28	8.5E−06	7.9E−05	0.0012	0.0012	9.27	138.66	145.36
18	11	9	26	27	8.5E−06	7.1E−05	0.0011	0.0012	8.35	124.32	140.17
19	9	7	25	25	6.9E−06	5.5E−05	1.0E−03	0.0011	7.93	146.10	158.63
20	8	5	24	24	6.2E−06	3.9E−05	9.7E−04	0.0011	6.38	157.79	171.32
21	7	5	22	23	5.4E−06	3.9E−05	8.9E−04	1.0E−03	7.29	165.30	187.63
22	6	5	22	22	4.6E−06	3.9E−05	8.9E−04	9.7E−04	8.50	192.85	209.39
23	4	4	18	19	3.1E−06	3.1E−05	7.3E−04	8.4E−04	10.20	236.68	271.25

$T_{CLEAR}(N)$ is the number of fatal crashes involving N (meaning n or more) vehicles, $\boldsymbol{\rho}_{CLEAR}(N)$ is $T_{CLEAR}(N)/T_{CLEAR}(1)$, and R_{RAIN} is $\boldsymbol{\rho}_{RAIN}(N)/\boldsymbol{\rho}_{CLEAR}(N)$, etc.

the clear weather case. The increases are steep for RAIN and yet steeper for SNOW and FOG.

3.3. Interpreting results as absolute crash risks

Fig. 4 is based exclusively on data for fatal crashes, so it cannot provide direct information on the probability of a crash occurring as a function of atmospheric conditions. The relating crash risk to weather has been the subject of many studies. Eisenberg and Warner (2005) linked 1975–2000 FARS data to daily state weather data and other data to investigate effects of snowfalls on crashes, injuries, and fatalities. They found that snow days had fewer fatal crashes than dry days but more nonfatal-injury crashes and property-damage-only crashes. The finding that snow is associated with reduced risk of a fatal crash is additionally supported by Evans (2004, P98–118). Eisenberg (2004) reports an increase in fatal crashes after rain that is larger as the time since the last rain increases. A drop to below average values occurs a few dry days after rain. It is suggested that the rain could cause increased caution that persists for a few days and also that the rain washes away oil that accumulates on roads during dry periods leading to reduced tire adhesion. Brodsky and Hakkert (1988) reported a larger increase in crashes in rain on days following long dry spells. Sun, Hu, Habib, and Magri (2011) reported higher crash risk and a higher injury risk during rain, but differences strongly depended on the type of highway, location of the highway, time of day, crash severity, and crash characteristics.

The literature justifies the following two conclusions. First, there is clear evidence that weather affects crash risk. Second, while effects are clear, they are not larger than, say, a factor of 2. If we make the assumption that weather does not affect fatal crash risk by more than a factor of 2, then Fig. 4, to within a factor less than 2, gives how a driver's risk of being involved in a fatal crash with N or more vehicles depends on environmental conditions.

So, for example, we conclude that $R_{SNOW}(10) = 23.48$ reliably establishes that when it is snowing, a driver's probability of being involved in a fatal crash with 10 or more vehicles is at least 11 times the probability when it is clear. Fig. 4, based exclusively on fatality data, establishes that the risk that a driver is involved in a fatal crash involving large numbers of vehicles is enormously increased when it is snowing or foggy.

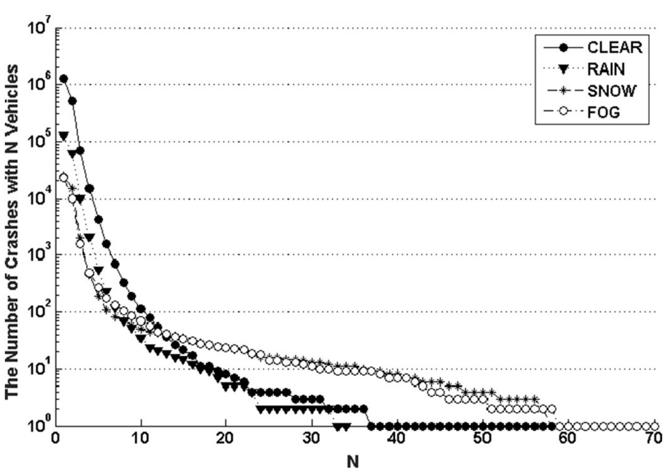

Fig. 2. $T(N)$, the number of fatal crashes with n or more vehicles versus N, where N means n or more vehicles involved in the crash.

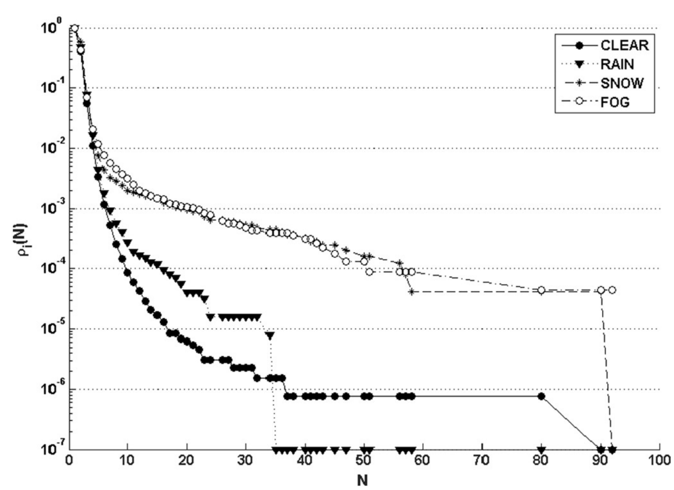

Fig. 3. The fraction of crashes, $\boldsymbol{\rho}_i(N)$ involving n or more vehicles versus N for each of the 4 atmospheric conditions (i = CLEAR, RAIN, SNOW, and FOG). N means the number of fatal crashes with n or more vehicles.

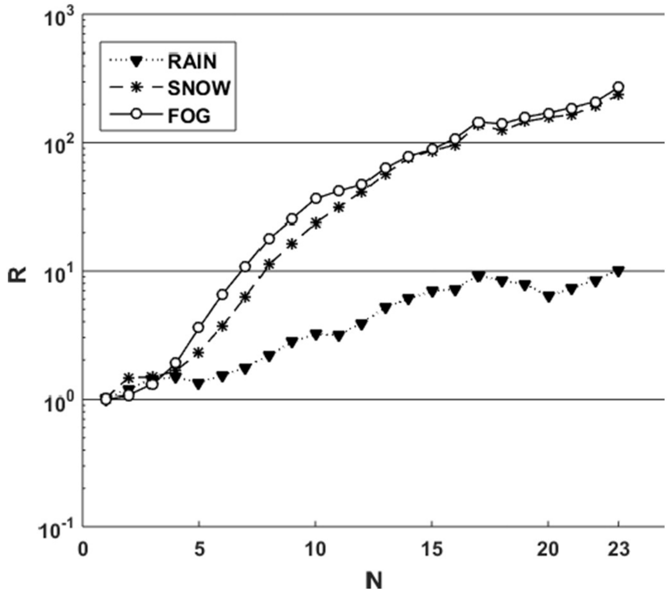

Fig. 4. Ratio for adverse weather to clear weather versus N, where N means n or more vehicles involved in the fatal crash.

3.4. Driver deaths per fatal crash

From Table 2 the number of driver deaths per fatal crash is computed and plotted in Fig. 5.

FARS defines a fatal crash as one involving a motorized vehicle in which at least one road user is killed. Table 1 implies that in 33.9% of fatal crashes no drivers are killed. This is why so many values of driver deaths per crash are less than 1.

The average number of deaths per fatal crash, as is to be expected, increases with N for all atmospheric conditions.

The increase is least for RAIN, for which the ratio exceeds one only when there are more than 17 vehicles involved in the crash, compared to 7 for CLEAR, 11 for SNOW, and 5 for FOG. This suggests drivers are reducing speeds when it is raining, which explains why $R_{RAIN}(N)$ increases so much less with increasing N than for the other adverse atmospheric conditions (Fig. 4). Direct evidence of lower speeds in rain is provided by Edwards (1999) who found lower severities in rain compared with fine weather.

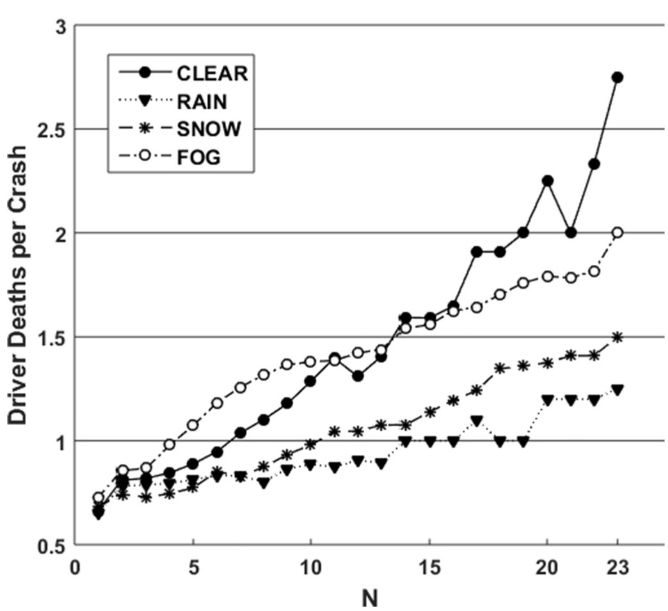

Fig. 5. Driver deaths per fatal crash versus N, where N means n or more vehicles involved in the fatal crash.

Similar comments apply for snow. We interpret the slower increase for RAIN and SNOW in the number of drivers killed per fatal crash as the number of vehicles involved increases to reflect speed reductions. Although fatal crashes involving very large numbers of vehicles occur, fewer drivers are killed because traffic is traveling at lower speeds.

The results for CLEAR and FOG are similar to each other, but very different from RAIN and SNOW. The similarity of the CLEAR and FOG results suggests that drivers are not slowing when it is foggy. There is evidence supporting this. Investigating the effect of fog in a simulator study, Snowden, Stimpson, and Ruddle (1998) concluded that because of perceptual effects, fog led to speed increases. Broughton, Switzer, and Scott (2007) simulated car following under reduced visibility and found fog conditions separated participants into a group that stayed within visible range of the lead car, even though this involved headways that are considered unsafe. Also, using Florida crash data, Abdel-Aty, Ekram, Huang, and Choi (2011) concluded that, compared to crashes under clear-visibility, fog, and smoke related crashes tend to result in more severe injuries and involve more vehicles.

3.5. Time trends

During the 40-year period covered by this study many changes occurred, including a reduction in fatal crashes in the United States from 38,594 in 1975 to 29,989 in 2014. This 22% decline is modest compared to the more than 80% declines reported in other countries (Evans, 2014). This contrast provides clear evidence that declines are generated mainly by changes in driver behavior and public policy addressing driver behavior, and not by vehicle-technology changes, as these are similar among different motorized countries.

Because the main focus of this paper is on what happens given that a fatal crash occurs, changes in absolute numbers do not materially affect conclusions. However, there is still much interest in examining how some characteristics have changed over four decades.

Fig. 6 shows how the probability that a fatal crash involves N or more vehicles varies over the study period. An important observation is that the percent of fatal crashes involving 2 or more vehicles remained remarkably constant at close to 40%. In other words, the percent of fatal crashes that were single-vehicle crashes remained close to 60%. More specifically, all 40 annual values were between 55.7% and 61.8%

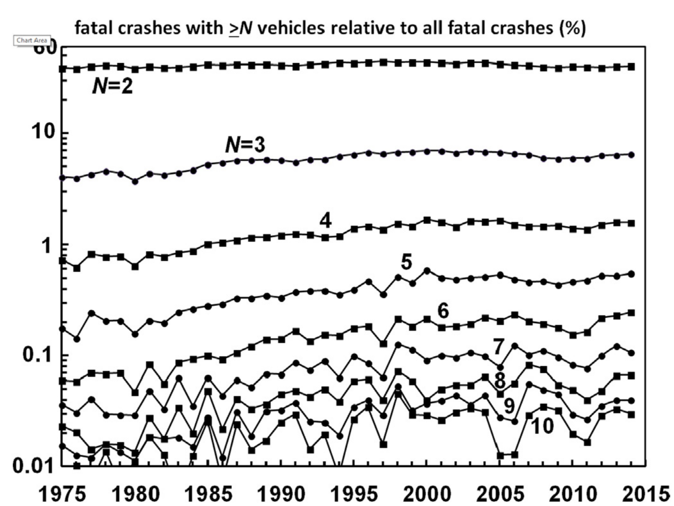

Fig. 6. The number of fatal crashes in indicated calendar year involving N or more vehicles divided by all fatal crashes in the indicated calendar year ($\times 100$) from 1975 to 2014.

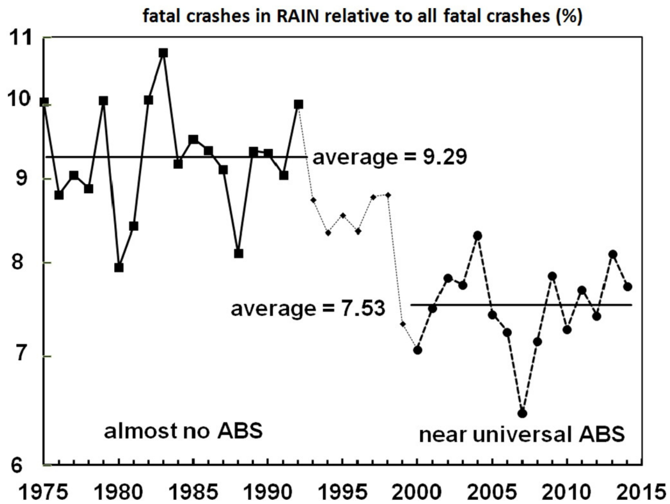

Fig. 7. The number of fatal crashes in rain relative to all fatal crashes from 1975 to 2014.

(average = 58.8%, std. dev = 1.4%). This robust basic fact was often downplayed and sometimes even ignored in the copious discussions over vehicle compatibility and vehicle downsizing. Consistently and stably, in well over half of all fatal crashes, there is no 'other vehicle,' so the outcome depended solely on the properties of a single-vehicle and its driver.

Given that a fatal crash occurs, the probability that it involves a large number of vehicles drifts in time erratically towards higher values. We have no explanations beyond the wildly speculative involving increasing speeds.

We examined the percent of all fatal crashes that occurred under each of the adverse weather conditions. The percent of crashes that occurred in SNOW, (1.65 ± 0.27)%, and FOG, (1.52 ± 0.26)%, remained remarkably constant over the 40-year time span, with no indication of any trend or other notable effect. However, for RAIN there was a clear downward trend (Fig. 7), with 10.0% of fatal crashes occurring in rain in 1975 compared to 7.7% in 2014. While a regression equation provided a reasonable fit to the 40 data points (r squared = 0.55), Fig. 7 reflects a different representation. The horizontal lines 1975–1992 (pre-ABS) and 2000–2014 (post-ABS) correspond to two relatively constant periods. Indeed, the least squares fit to these subsets of the data are almost indistinguishable from the horizontal lines.

Prior to 1992 few new vehicles were equipped with antilock brakes (ABS), so only a much smaller proportion of ABS-equipped vehicles were on the roads. From the mid-1990s onwards ABS increasingly became standard equipment in nearly all new vehicles, although it was not required by NHTSA regulation until 2012. NHTSA's own research had concluded that "ABS has close to a zero net effect on fatal crash involvements" (Kahane & Dang, 2009). If we assume that ABS did not affect crash risk under CLEAR conditions, then Fig. 7 implies that crash risk in RAIN was lower in the post-ABS period than in the pre-ABS period. This is so only if the amount of rain did not change between the periods. This is indeed so, as is confirmed by data from the National Oceanic and Atmospheric Administration, National Centers for Environmental Information (NCEI) (2016). The average precipitation in the contiguous states in the post-ABS period did indeed nominally decline compared to in the pre-ABS period, but by an inconsequentially small percent, from 30.67 in. to 30.24 in.

An interpretation of the findings in Fig. 7 is that ABS is reducing fatal crash risk in rain by $(9.29–7.53)/9.29 = 19\%$. This augments earlier findings that ABS reduces risk on wet roads. Kahane and Dang (2009) found a significant 12% reduction in fatal collisions with other vehicles on wet roads. Evans (1995) found a 13% lower crash risk when it is raining. For two-vehicle crashes, Evans and Gerrish (1996) found that for wet roads, ABS reduced the risk of crashing into a lead vehicle by (32 ± 8)% but increased the risk of being struck in the rear by (30 ± 14)%. While the lead vehicle was known to have ABS, the random following vehicle in the 1992 and 1993 data used almost certainly did not have ABS, so the effect could be more net beneficial as all vehicles acquire ABS.

If ABS did reduce fatal crash risk when it is raining by 19%, but had no effect under other environmental conditions, the net effect on all fatal crashes would a reduction of $0.19 * 9.29/100 = 1.8\%$, too small an effect to be detected in aggregate data.

For fatal crashes in RAIN, we found no systematic or notable effects dependent on the number of involved vehicles. Examining effects for large numbers of involved vehicles were limited due to small numbers of cases.

4. Limitations

A major limitation of this study, in common with all such studies, is that we do not know the driving speed of the vehicles prior to any participation (such as speed reduction or brake application) in the crashes. Such information is recorded in an Electronic Data Recorder fitted to most vehicles. However, legal constraints prohibit access by the police coding the inputs to FARS data. Another limitation is that the collected data of 40 years from FARS 1975–2014 is still not sufficient. However, it is the first study to investigate how weather affects involvement and driver fatality risk in crashes involving very large numbers of vehicles.

5. Summary of results

(1) Crashes involving more than 35 vehicles are more likely to occur when it is snowing or in fog.
(2) If a vehicle is involved in a fatal crash when it is raining, the crash is three times as likely to involve 10 or more vehicles than when it is clear.
(3) If a vehicle is involved in a fatal crash when it is snowing, the crash is 24 times as likely to involve 10 or more vehicles than when it is clear.
(4) If a driver is involved in a fatal crash when there is fog, the crash is 35 times as likely to involve 10 or more vehicles compared than when it is clear.
(5) If instead of selecting crashes involving 10 or more vehicles we had chosen crashes involving 20 or more vehicles, the risk ratios would be 6 for rain, 158 for snow, and 171 for fog.
(6) These risk ratios are likely the largest reported in traffic safety research.
(7) Driver deaths per fatal crash increases slowly with increasing numbers of involved vehicles when it is snowing or raining, but more steeply when weather is clear or foggy.
(8) Drivers reduce speed when it is snowing or raining, but no indication of similar reductions when foggy.

6. Conclusions

In order to reduce the risk of involvement in crashes involving large numbers of vehicles, drivers must reduce speed in fog, and in snow or rain, reduce speed by even more than they already do. Future works on exploring and validating more effective countermeasures to help drivers reduce their speed in adverse weather conditions are strongly suggested. Images of multi-vehicle crashes could be used in messages to encourage drivers to slow down, and expand the message to stress that speed is the most central factor in all types of crashes under any conditions.

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