A GIS-based Matched Case–control Study of Road Characteristics in Farm Vehicle Crashes

Shabbar I. Ranapurwala,[a] *Elizabeth R. Mello,*[a,b] *and Marizen R. Ramirez*[a]

Background: Farm vehicle-related crashes (crashes) are hazardous for farm and non-farm vehicle users; however, most studies examine risk factors of injury given a crash, and shed little light on risk factors of crashes. We evaluated the association of road sinuosity and gradient with crashes in nine Midwestern States from 2005 to 2010.
Methods: We collected crash data from the state departments of transportation, and road segment data from the Environmental Sciences Research Institute. We measured gradient and sinuosity of road segments using ArcGIS. A road segment with a crash was defined as a case (n = 6,848), and that without a crash was defined as a control. Controls were matched to cases by ZIP code, road type, and length in 1:1 (controls = 6,808) matching scheme. In addition, a 1:many control matched scheme was employed such that all road segments adjacent to the case would serve as controls (n = 24,390). We computed odds ratios (OR) and 95% confidence intervals (CIs) using multivariable conditional logistic regression.
Results: The adjusted OR of a crash on a road segment with 6%–10% gradient was 0.60 (95% CI: 0.49, 0.75) as compared with a leveled (<1% gradient) road segment. Compared with a straight (<1% sinuosity) road segment, the adjusted OR of a crash on a road segment with 6%–10% sinuosity was 0.38 (95% CI: 0.29, 0.52).
Conclusions: Roads with increased gradient and sinuosity had fewer farm crashes. These associations may be due to cautious driving behaviors on curvy or steep roads and road side signage alerting drivers of impending curve or grade.

(*Epidemiology* 2016;27: 827–834)

BACKGROUND

Although vital to our national economy and sustenance, agriculture is a hazardous industry with high risk of occupational injuries. From 2005 to 2009, the occupational fatality rate in agriculture, forestry, and fishing combined was 29.2 per 100,000 full-time employees, the highest among all occupations in the US.[1] Transportation is the leading cause of occupational deaths in the agricultural industry. In 2013, 123 agricultural workers were fatally injured[2] and more than 42% of fatal agricultural injuries (n = 52) were attributed to transportation incidents.[3]

Agricultural workers engage regularly in transportation-related tasks, operating large machinery such as tractors, combines, pickup truck, or trailers on public roads when traveling between home, farmstead, and markets. Maneuvering large, slow-moving farm equipment on narrow, high-speed rural roads could be hazardous, especially because roadways are not outfitted for large farm equipment and there is usually a big speed differential between a farm and non-farm vehicle. These are ripe conditions for farm vehicle-related crashes (from here forward "crashes" or "farm crashes" unless otherwise stated).[4]

Farm crashes, like all motor vehicle crashes, occur in both rural and urban settings[5–9]; however, between 2005 and 2008, 2% of farm crashes involved a fatality in the nine Midwestern states as compared with 0.45% fatalities in crashes involving other motor vehicle crashes.[10–18] Other research shows that majority of farm crashes involved multiple vehicles,[5,19] and the non-farm vehicle occupants were more likely to be injured[4] or killed[20] than farm vehicle occupants. Thus, farm crashes are hazardous to all motorists, and research on farm crashes contributes to the larger goal of roadway safety.

Prior studies of farm crashes have focused primarily on identifying risk factors of injury after the farm vehicle crash has occurred. Potential risk factors include driver-, vehicle-, and crash-level characteristics including road characteristics and environmental conditions like lighting, season, time of the day, and day of the week.[4,20–22] Such case-only studies estimate the risk of injury given a crash, not the risk of a crash. In addition, previous studies are less generalizable because their samples were restricted to specific states,[4,19] or specific countries other than the United States,[20,21] or because data source included only tractors.[22] Our current research focuses on identifying roadway design factors that may help address primary farm crash prevention efforts and roadway safety in general.

Submitted 31 July 2015; accepted 25 July 2016.
From the [a]Department of Occupational and Environmental Health, Injury Prevention Research Center, The University of Iowa, Iowa City, IA; and [b]Department of Epidemiology, College of Public Health, The University of Iowa, Iowa City, IA.
Supported by Grant U50 OH007548-11 from the National Institute of Occupational Safety and Health for the Great Plains Center for Agricultural Health.
The authors report no conflicts of interest.
SDC Supplemental digital content is available through direct URL citations in the HTML and PDF versions of this article (www.epidem.com).
Correspondence: Shabbar I. Ranapurwala, Injury Prevention Research Center, University of Iowa, 200 Newton Road, 2198WL, Iowa City, IA. E-mail: shabbarkaid@gmail.com.

ISSN: 1044-3983/16/2706-0827
DOI: 10.1097/EDE.0000000000000542

Among roadway design characteristics that influence crashes, the role of curvature and grade of roads has long been debated. Early studies have shown that greater curvature and gradient are associated with single vehicle fatal road-side-run-off crashes,[23–25] and installing reflectors at high curvature sites decreased crash incidence.[26] Others argue that curved roads and roads with up-hills and down-hills could actually be safer than straight leveled roads.[12,22,27]

The early studies on road curvature and gradient were conducted by personally visiting each crash site and comparing the crash road segment with a previous segment of road.[23–25] Now, with geographical information systems (GISs), the need to go to a crash site and taking measurements manually is eliminated. GIS allows remote spatial mapping of crashes and contains data on all public access road segments across the United States.[5,28] We can also measure the sinuosity (curvedness) and gradient of road segments with high precision and low cost. In this study, we used GIS to measure the sinuosity and gradient of all road segments across nine Midwestern states of the United States, and evaluated the relationship of these road characteristics with farm crashes from 2005 to 2010.

METHODS

We used a matched case–control study design to estimate the association of gradient and sinuosity of road segments with farm crashes from 2005 to 2010. This multistate study included nine Midwestern US states with strong agricultural industries and high annual incidence of farm crashes—Iowa, Illinois, Kansas, Minnesota, Missouri, Nebraska, North Dakota, South Dakota, and Wisconsin.

A case was defined as a public access road segment, within the nine study states, that had a farm crash between January 1, 2005, and December 31, 2010. A control was defined as a public access road segment, within the nine study states, that did not have a farm crash during the same time. If a road segment had multiple crashes, then we counted as many case segments as the number of crashes. The study was determined non-human subjects research by the University of Iowa Institutional Review Board because of use of deidentified data.

Data Sources

Public access road segment data and their elevation from the sea level were collected from Environmental Services Research Institute (ESRI). Roads are divided into segments based on Census Feature Class Codes for roads.[29] The data include ZIP code, road type, speed limits based on road types, state, and a unique identifier for each road segment. Length of the road segments was calculated using ArcGIS tools. A separate set of data that provides information on the terrain of the region, also known as raster data, was used to calculate the elevation for each road segment. These data were used to calculate gradient and sinuosity of road segments.

The departments of transportation from the nine states provided administrative crash data from January 1, 2005, to December 31, 2010. Crashes included in these data occurred on public access roadways and were reported to the police. Crash reporting criteria include death, injury, or property damage of more than \$500–\$1,500, depending on the state. In six of the nine states (Iowa, Illinois, Minnesota, Nebraska, North Dakota, and South Dakota), law enforcement officers collected characteristics of crashes, including the geocoordinates (x and y coordinates) of the crash location using a handheld GPS device at the time of the crash. Law enforcement officers from Wisconsin, Kansas, and Missouri collect the name of the street where the crash occurred and the distance of this location from the nearest intersection. Using addresses from these three states and x–y coordinates from the other six states, crashes were geolocated on the road segments. Geocoding was conducted using ArcGIS 10.2. Detailed methods used to coalesce the nine state data and spatially locate the crash locations are discussed by Harland et al.[5] The crash data, the road segment, and the raster data were combined using a spatial overlays to create a final dataset for analysis.

Grade and Sinuosity

The exposures of interest, gradient and sinuosity, were not available from ESRI, hence were calculated. Gradient was defined as rise over run, or the percent (%) change in the elevation divided by the length of the road segment.[30] If a road segment AB (Fig. 1) has length l with a minimum elevation of h_1, a maximum elevation of h_2, and Δh is the difference in the elevation ($h_2 - h_1$), then, gradient = $(\Delta h/l) \times 100$.

Sinuosity was defined as the percent (%) deviation of a road segment from a straight line.[31] This was calculated by dividing the length of a road segment, l, by the straight distance, d, between the end points of the road segment AB (Fig. 2), where $x1$, $y1$, $x2$, and $y2$ are coordinates of points A and B, such that $d = |x1y1 - x2y2|$, and sinuosity = $[(l/d) - 1)] \times 100$.

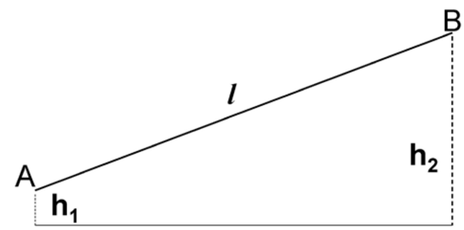

FIGURE 1. Road segment AB with length l, maximum elevation h_2, minimum elevation h_1.

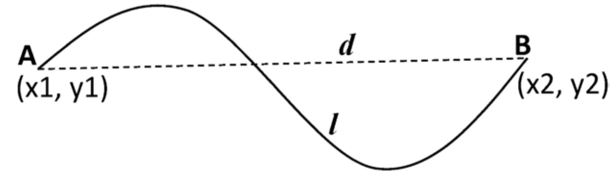

FIGURE 2. Road segment AB with length l, where coordinates for point $A = (x1, y1)$ and $B = (x2, y2)$.

A road segment with zero % gradient (i.e., $\Delta h = 0$) will be a flat road segment. While a road segment with zero % sinuosity ($l = d$) will be a straight road segment. Both gradient and sinuosity were right skewed data (i.e., more flat or leveled roads and more straight roads). Due to this and based on previous research, we categorized gradient as <1%, 1%–5%, 6%–10%, and >10%, and categorized sinuosity as <1%, 1%–5%, 6%–10%, 11%–20%, and >20%.[23–25]

Matching

We drew a directed acyclic graph (eFigure 1; http://links.lww.com/EDE/B96) to assess potential confounding in the exposure–outcome relationships. The minimal sufficient set of covariates included length of the road segment, road type, and ZIP code. ZIP code represents population density, and hence may also represent traffic density. A 1:1 control matched dataset was created using SAS code provided by Mounib and Satchi,[32] such that we sought matched controls for cases with an exact ZIP code match, and category-matched road type and road segment length. Road type had seven broad categories based on the Census Feature Class Code classification for roadways[29] and road segment length was categorized in 100 m increments of length, as >0 to 100 m, >100 to 200 m, >1,500 to 1,600, and >1,600 m. Wherever an exact ZIP code matched control was not found, we used the neighboring ZIP code.

However, with the above matching scheme, selected controls could include road segments where no farm vehicles were ever driven. A better matching variable would be farm vehicle density; however, these data were not collected by departments of transportation. We addressed this by creating a second 1:n matched dataset where controls were matched to cases based on the location of case segments rather than ZIP code. Hence, all road segments that were connected to a case segment were selected as controls (one or more) for that case segment (Fig. 3). This increased the likelihood that the control road segments would have similar farm vehicle density as cases. This method has been used previously in studies of single motor vehicle roadside run-off crashes.[23–25]

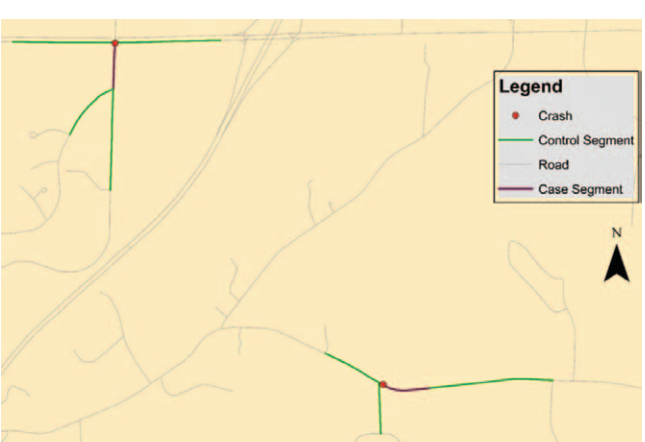

FIGURE 3. Controls segments (in green) matched to case segments (in magenta) based on location.

Statistical Analysis

To measure the associations of gradient and sinuosity with farm crashes, we compared matched cases and controls using multivariable conditional logistic regression models, conditional on the matching factors (i.e., ZIP code, road type, and length of the road segment). Previous studies assessing the relationship between road geometry and motor vehicle crashes have only been conducted in single vehicle fatal crashes.[23–25] We anticipated seeing an effect measure modification by single or multiple crashes, and fatal or nonfatal crashes. To address this, we conducted separate analyses for fatal, nonfatal, single vehicle, and multiple vehicle farm crashes.

We report crude and adjusted odds ratios (ORs) with 95% confidence intervals (95% CIs). We conducted all the analyses using SAS 9.4, SAS Institute, Cary, NC.

RESULTS

There were 6,491,811 road segments, and 7,094 farm crashes in the nine states from 2005 to 2010. About 3.5% of all farm crashes (n = 246) had missing locational data (x and y coordinates or address) and were therefore excluded from the analyses. After geocoding these crashes, there were 6,723 road segments, 93 of these had two crashes each, three road segments had three crashes each, and four road segments had four crashes each. Hence, overall there were 6,848 cases, representing 0.1% of all road segments.

The mean length of all road segments from nine states was 321 m (SD 388 m). The mean sinuosity was 2.1% (SD 17.9), and the mean gradient was 2.7% (SD 5.0). Although Illinois had the most crashes (n = 1,190) from 2005 to 2010, Iowa had the highest incidence rate at 0.2% or 20 crashes per 10,000 road segments. South Dakota had the fewest crashes (n = 226) and the lowest incidence rate of crashes from 2005 to 2010 at 0.06% or six crashes per 10,000 road segments. Road segments with crashes had a lower mean grade and sinuosity than road segments without crashes (Table 1).

We found 6,808 matched control road segments for 6,848 case segments while conducting 1:1 matching by ZIP code, road type, and segment length. When a control segment was selected based on its connectedness to the case segment (Fig. 3), a total of 24,390 control road segments were matched to 6,848 cases, ranging from 1 to 17 controls per case (median = 5).

Adjusted ORs from the matched analyses suggested a potential dose–response relationship such that increases in gradient and sinuosity were associated with lower odds of crashes (Table 2). Relative to a flat road segment (with less than 1% gradient), the adjusted OR of farm crashes on a road segment with more than 10% gradient was 0.60 (95% CI: 0.49, 0.75) in the 1:1 matched analysis, and was 0.75 (95% CI: 0.61, 0.92) in the 1:n matched analysis (Table 2).

TABLE 1. Exposure and Covariate Distribution for Cases, Controls, and All Non-crash Road Segments[a]

Variable	Units	Cases (n = 6,848)	1:1 Matched Controls (n = 6,808)	1:*n* Matched Controls (n = 24,390)	Non-crash Segments (n = 6,484,963)
		Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
Sinuosity	Percent (%)	0.8 (5.6)	1.6 (7.2)	0.9 (7.7)	2.1 (18)
Grade	Percent (%)	2.4 (3.7)	2.6 (4.0)	2.5 (3.9)	2.7 (4.2)
Segment length	Meters (m)	663 (487)	634 (485)	503 (472)	320 (388)
	Categories	n (%)	n (%)	n (%)[b]	n (%)
Road type	Primary highway with limited access	70 (1.0)	70 (1.0)	220 (0.9)	123,368 (1.9)
	Primary road without limited access	890 (13)	859 (13)	2,214 (9.8)	197,515 (3.0)
	Secondary connecting road	2,356 (34)	2,348 (34)	5,994 (25)	748,777 (12)
	Local, neighborhood, rural road	3,506 (51)	3,506 (51)	15,710 (64)	5,223,100 (80)
	Vehicular trail	0 (0)	0 (0)	2 (0.01)	5,961 (0.1)
	Road with special characteristics	19 (0.3)	19 (0.3)	158 (0.6)	140,758 (2.2)
	Road as other thoroughfare	7 (0.1)	6 (0.1)	85 (0.3)	45,484 (0.7)
State	Illinois	1,190 (17)	1,180 (17)	4,309 (18)	1,293,501 (20)
	Iowa	1,168 (17)	1,162 (17)	4,412 (18)	576,903 (8.9)
	Kansas	644 (9.4)	640 (9.4)	2,491 (10)	737,185 (11)
	Minnesota	824 (12)	820 (12)	3,140 (13)	818,736 (13)
	Missouri	1,014 (15)	1,006 (15)	3,410 (14)	1,028,683 (16)
	Nebraska	510 (7.4)	508 (7.5)	2,067 (8.5)	513,990 (7.9)
	North Dakota	246 (3.6)	246 (3.6)	1,004 (4.1)	372,496 (5.7)
	South Dakota	226 (3.3)	226 (3.3)	946 (3.9)	360,069 (5.6)
	Wisconsin	1,026 (15)	1,020 (15)	2,611 (11)	783,400 (12)

[a]A road segment with a farm crash is defined as a case segment, and a road segment without a farm crash is defined as a control segment.
[b]Seven road segments had missing road type information.
% indicates percent of road segments; n, number of road segments.

Similarly, compared with a straight road (<1% deviation), the adjusted OR of farm crashes on a road segment with 6%–10% deviation was 0.38 (95% CI: 0.29, 0.52) in the 1:1 matched analysis, and was 0.76 (0.56, 1.01) in the 1:*n* matched analysis (Table 2). Even though the variation in the effect size is large, all the analyses suggest a common interpretation that fewer crashes occurred on graded and sinuous roads than flat and straight roads.

When we assessed potential effect measure modification by type of crashes, we observed that compared with a flat road segment, the ORs of single vehicle crashes on a road segment with 6%–10% grade were 1.1 (95% CI: 0.7, 1.8) and 1.4 (95% CI: 0.90, 2.1) in the 1:1 and 1:*n* analysis, respectively (Table 3). These results were similar to those observed in single vehicle fatal road side run-off motor vehicle crashes reported in previous studies.[23–25] But, this was contrasting to the relationship between gradient and multiple vehicle crashes where, compared with a flat road segment, the ORs of crashes on a segment with 6%–10% gradient were 0.64 (95% CI: 0.54, 0.75) and 0.73 (95% CI: 0.63, 0.86) in the 1:1 and 1:*n* analysis, respectively (Table 3). Road segments with greater than 1% sinuosity were associated with lower odds of single and multiple vehicle crashes (Table 3).

Nonfatal farm crash odds were lower among road segments with more than 1% gradient and sinuosity (eTable 1; http://links.lww.com/EDE/B96). However, we observed inconsistent relationships between fatal crashes and gradient or sinuosity (eTable 1; http://links.lww.com/EDE/B96), perhaps because of small number of fatal farm crashes overall during the 6-year period.

DISCUSSION

This is the first study to use GIS-based roadway data to measure sinuosity and gradient of road segments and assess their relationships with farm crashes. The results indicate that increased sinuosity and gradient of road segments are associated with a reduced risk of crashes involving farm vehicles. However, these results were not consistent across all types of farm crashes. More single vehicle crashes were observed with increased gradient of road segments, and the relationships between fatal crashes and gradient or sinuosity of road segments were inconclusive.

These results may seem counterintuitive to popular beliefs and literature.[23–25] Earlier studies that measured curvature and gradient, and examined their relationship with crashes, were exclusively conducted in fatal single motor

TABLE 2. Crude and Adjusted Measures of Association (and 95% CI) of Road Segment Gradient and Sinuosity with Farm Crashes

Exposure Categories	Cases	Controls	Crude OR (95% CI)	Adjusted OR[b] (95% CI)
	Matched Data (1:1): 6,848 Cases: 6,808 Controls[a]			
Grade				
<1%	3,030	2,889	Referent	Referent
1% to < 6%	3,002	2,926	0.98 (0.91, 1.1)	0.93 (0.85, 1.0)
6%–10%	569	686	0.79 (0.70, 0.89)	0.68 (0.58, 0.79)
>10%	247	307	0.77 (0.64, 0.91)	0.60 (0.49, 0.75)
Sinuosity				
<1%	5,977	5,462	Referent	Referent
1% to <6%	672	892	0.69 (0.62, 0.77)	0.63 (0.56, 0.70)
6% to 10%	71	151	0.43 (0.329, 0.57)	0.38 (0.29, 0.52)
11% to 20%	70	153	0.42 (0.31, 0.57)	0.35 (0.26, 0.47)
>20%	58	150	0.35 (0.26, 0.48)	0.29 (0.21, 0.40)
	Matched data (1:*n*[c]): 6,848 Cases: 24,390 Controls[d]			
Grade				
<1%	3,030	10,968	Referent	Referent
1% to <6%	3,002	10,212	1.06 (1.01, 1.13)	0.97 (0.90, 1.1)
6%–10%	569	2,191	0.94 (0.85, 1.0)	0.78 (0.68, 0.91)
>10%	247	1,019	0.88 (0.76, 1.0)	0.75 (0.61, 0.92)
Sinuosity				
<1%	5,977	21,377	Referent	Referent
1% to <6%	672	2,155	1.1 (1.0, 1.2)	0.98 (0.88, 1.1)
6% to 10%	71	318	0.80 (0.62, 1.0)	0.76 (0.56, 1.0)
11% to 20%	70	299	0.84 (0.64, 1.1)	0.75 (0.56, 1.0)
>20%	58	241	0.86 (0.65, 1.2)	0.82 (0.59, 1.1)

[a]Matched for ZIP code, road type, and segment length.
[b]Conditionally adjusted for ZIP code, road type, and segment length.
[c]Number of controls per case range from 1 to 17, median = 5.
[d]Matched for geographic location, such that all adjacent road segments to a case are selected as controls for that case segment, and adjusted for length and type of the road segment.
RR indicates risk ratio.

vehicle roadside run-off crashes.[23–25] These studies consistently concluded that curvature of >6% along with downward grade was associated with fatal single motor vehicle roadside run-off crashes. After restricting our sample to single vehicle crashes (fatal and nonfatal), we found that increasing grade was associated with higher odds of single vehicle crashes, which is similar to earlier studies.[23–25] However, all other results from our study conflict with the earlier studies; we found that increased sinuosity (curviness) is associated with a lower odds of all farm crashes and increasing gradient is associated with lower odds of multiple vehicle farm crashes. This may be because we examined altogether different types of crashes than those examined in the above-mentioned studies. First, our analyses involved all farm crashes and not fatal single motor vehicle crashes. Farm crashes on public roads more commonly involve multiple vehicles than single vehicles, and more commonly than not, the other vehicle is a non-farm vehicle.[5,19] In this study, too, 87% cases (n = 5,717) were multiple vehicle crashes. The most common form of crash in the single vehicle fatal crashes examined by previous studies were rollover or run-off crashes,[23–25] and in one study the cause of death was drowning.[25] The most common factor involved in farm crashes is failure to reduce speed by the non-farm vehicle.[19,33,34] Because the farm vehicle is slow moving, the non-farm vehicle, which is at a higher speed, approaches the farm vehicle very rapidly.[4] This sudden approach is usually unexpected for the non-farm vehicle drivers, and sometimes results in a rear end crash or side swipe in the same direction, the most common types of farm crashes.[4,5,20]

Our results may be best explained by driver behavior, such as increased caution, when encountering curves or hills. In his book *Traffic*, Vanderbilt[27] explains how drivers seem to react to dangerous roads with caution, which was especially true in Sweden where crash rates decreased after the whole country changed from left-hand to right-hand driving in 1967. In another simulation study, drivers who were asked to drive on roads where roadside objects and vegetation were in close proximity to the roads, drove at considerably slower speeds, and away from the edge of the road, as compared with roads

TABLE 3. Adjusted Measures of Association (and 95% CI) of Road Segment Gradient and Sinuosity with Single and Multiple Vehicle Farm Crashes[a]

Exposure Categories	1:1 Matched Single Vehicle Crash Data: 882 Cases: 880 Controls[b]		1:1 Matched Multiple Vehicle Crash Data: 5,717 Cases: 5,679 Controls[b]	
	Cases/Controls	Adjusted OR[c] (95% CI)	Cases/Controls	Adjusted OR[c] (95% CI)
Grade				
<1%	481/445	Referent	2,454/2,348	Referent
1% to <6%	312/363	0.74 (0.58, 0.95)	2,554/2,432	0.95 (0.86, 1.1)
6%–10%	63/51	1.1 (0.72, 1.8)	492/615	0.64 (0.54, 0.75)
>10%	26/21	1.2 (0.57, 2.3)	217/284	0.55 (0.43, 0.69)
Sinuosity				
<1%	778/727	Referent	5,022/4,560	Referent
1% to <6%	80/91	0.73 (0.51, 1.0)	545/759	0.59 (0.52, 0.67)
6%–10%	10/21	0.36 (0.15, 0.78)	53/124	0.34 (0.25, 0.48)
11%–20%	6/21	0.21 (0.08, 0.53)	55/119	0.36 (0.26, 0.50)
>20%	8/20	0.39 (0.17, 0.89)	42/117	0.27 (0.18, 0.39)
	1:n[d] Matched Single Vehicle Crash Data: 882 Cases: 3,991 Controls[e]		1:1 Matched Multiple Vehicle Crash Data: 5,717 Cases: 20,399 Controls[e]	
Grade				
<1%	481/2,262	Referent	2,454/8,706	Referent
1% to <6%	312/1,426	1.0 (0.82, 1.3)	2,554/8,786	0.97 (0.88, 1.1)
6%–10%	63/216	1.4 (0.90, 2.1)	492/1,975	0.73 (0.63, 0.86)
>10%	26/87	1.4 (0.76, 2.7)	217/932	0.70 (0.57, 0.87)
Sinuosity				
<1%	778/3,586	Referent	5,022/17,791	Referent
1% to <6%	80/299	0.97 (0.72, 1.3)	545/1,856	0.98 (0.87, 1.1)
6%–10%	10/37	0.80 (0.38, 1.7)	53/281	0.74 (0.54, 1.0)
11%–20%	6/35	0.51 (0.21, 1.3)	55/264	0.78 (0.57, 1.1)
>20%	8/34	0.77 (0.34, 1.8)	42/207	0.83 (0.58, 1.2)

[a]249 cases did not have information on the number of vehicles involved in the crash and hence were excluded from the above analyses.
[b]Matched for ZIP code, road type, and segment length.
[c]Conditionally adjusted for ZIP code, road type, and segment length.
[d]Number of controls per case range from 1 to 17, median= 5.
[e]Matched for geographic location, such that all adjacent road segments to a case are selected as controls for that case segment, and adjusted for length and type of the road segment.
RR indicates risk ratio.

without roadside objects and vegetation.[35] Such behaviors support the hypothesis that drivers are cautious when driving on potentially dangerous roads.

Another explanation for these results, as suggested in the directed acyclic graph, may be the presence of curve and grade signs or pavement reflectors on roads that might be effectively improving driving behavior and reducing risk of crashes. We did not have data on curve or grade signs, hence we could not perform mediation analysis to evaluate direct and indirect relationships of sinuosity and gradient with farm crashes. However, this hypothesis is supported by an earlier study, where installation of pavement reflectors at curves reduced night time crashes.[26] Another national US study that examined crashes between farm vehicles and non-farm vehicles suggested that fewer fatal crashes occurred on curved and non-leveled road sections than on straight and leveled roads.[22]

It is not reasonable to eliminate straight and flat roads because they provide ease of driving and better visibility, but they may allow a driver to underestimate the danger due to slow-moving farm vehicles on rural roads. Additional studies that involve simulation[35] or naturalistic driving may be needed to understand driver behaviors in such conditions. Naturalistic driving studies may be best utilized by examining driver behaviors during near-misses instead of crashes because crash yield in such studies is often low.[36] This may allow us to develop and study the impact of focused interventions to increase driver awareness about slow-moving farm vehicles on rural roadways and promote cautious driver behavior. For example, we could study the effect of radio broadcasts of farm crash public service announcements[37] in a randomized study. Other interventions may include growing or not mowing vegetation around straight and flat roads[35] and erecting slow-moving vehicle signage on straight and flat roadsides on rural roads. County- or state-level interventions may also include providing information on farm crashes to new and old drivers while getting or renewing their driver's licenses. Such interventions may not only prevent farm crashes but also promote overall road safety.

Limitations

We made certain assumptions and considerations in the conduct and interpretation of this study. The definition of sinuosity assumes that two road segments that have the same deviation from a straight line, say 20%, have similar dimensions. This may not be true. A 20% deviant road segment may contain one long loop-like curve or may contain two small sinuous curves. Thus, the results cannot suggest which type of sinuous road makes drivers more cautious. This limitation also applies to the gradient definition. Second, the road segment data were from 2003; however, the crash locations are from 2005 to 2010. Even though it is reasonable to assume that road segments did not substantially change in the ensuing years to affect the outcome of this study, some changes in road segments could have occurred over this period that do not precisely reflect the crash conditions. Third, we did not have information about the direction of travel of the vehicles. The direction of travel may be an effect measure modifier in the gradient–farm crash relationship. A large slow-moving farm vehicle could pose different set of problems while going up or down a hill. Direction of travel, however, may not bias the results as it is not associated with road geometry.

Finally, unmeasured confounding may be a valid concern. Vehicular or individual factors may seem like potential confounders of the road segment sinuosity/gradient and farm crash relationship. To be a confounder, a covariate must be associated with both the exposure and the outcome, and must not be on a causal pathway between the exposure and outcome (not be caused by the exposure). Various vehicular and individual factors affect the incidence of motor vehicle crashes, however, they are either not associated with road segment gradient/sinuosity or are present because the roads are sinuous or graded (on the causal pathway). Thus, these factors are not confounders of the gradient/sinuosity–farm crash relationship. However, the proportion of some driver demographic factors may be differentially distributed among road segments with different gradient/sinuosity and those factors may also be associated with crashes. For example, the density of male drivers may be greater on graded and sinuous roads than on the flat and straight roads. In addition, we can assume that the density of male drivers on crash segments might be higher than on the control segments because crash rates among males are higher than in females.[38] In the current analyses, we could not adjust for the roadway male driver density because such data are not available.

We conducted quantitative bias analyses to assess the change in crude ORs when adjusting for the density of male drivers on roadways. This required two pieces of data. The first was the relationship between roadway density of male drivers and farm crash, which we assumed to be similar to the driver sex and motor vehicle crash relationship. The rate ratio of motor vehicle crashes comparing males and females is 1.3.[38] Since the overall rate of crashes is low (rare outcome),[38] the rate ratio approximates an OR of 1.3. We also observed that in our case segments, 78% vehicles involved in the crash had a male driver or passenger, while only 22% had female drivers or passengers. In addition, almost half of all drivers in the US are males,[38] assuming this for all noncrashes (controls), we get an OR of 3.5 for the association between roadway male driver density and farm crash. We considered ORs of 1.3 and 3.5 as the extremes of the association between roadway male driver density and farm crashes. We assumed two additional OR values of 2 and 3.

The second piece of information was the density of male drivers on flat roads (gradient <1%) and straight roads (sinuosity < 1%). Because about 50% of US drivers are males,[38] we fixed the density of male drivers on flat and straight roads at 0.5. While keeping this constant, we varied the density of male drivers on sinuous and graded roads from 0.1 to 0.9.

For varying ORs of roadway male driver density–farm crash relationship, varying densities of male drivers on sinuous and graded roads, and constant density of male drivers (0.5) on flat and straight roads, we calculated adjusted ORs of farm crashes comparing flat and straight road segments to segments with 6%–10% grade/sinuosity. Analyses were conducted for all farm vehicle crashes, single vehicle crashes, multiple vehicle crashes, fatal crashes, and nonfatal crashes, using excel spreadsheet of simple sensitivity analyses for unmeasured confounding with no effect measure modification by Lash et al.[39] The results (eFigures 2–11; http://links.lww.com/EDE/B96) suggest that barring some extreme values of confounder–outcome and confounder–exposure associations (plotted in gray color), the interpretations from our study would not have changed if we had controlled for the density of male drivers on road segments.

CONCLUSIONS

Contrary to popular belief, in this study, road segments with greater sinuosity and gradient had fewer farm vehicle crashes than straight and flat roads. We offer a few hypotheses to explain these relationships. Curvature and gradient warning signs on road segments may be forcing drivers of farm and non-farm vehicles to engage in cautious driver behaviors under seemingly difficult driving conditions (i.e., when on curvy, steep roads). The large sample from the multistate design of the study, the use of GIS for accurate exposure assessment, and the robustness of results are strengths of this study. The mechanism and implications of the results merit further research on driver behaviors and interventions that promote cautious and attentive driver behaviors.

ACKNOWLEDGMENTS

We thank Mitchell Greenan, MS, who helped us with GIS mapping and Hongqian Wu, MPH, who cleaned the DOT data. We thank the advisory council of the Great Plains Center for Agricultural Health for their continued guidance and support. We also thank Dr. Tim Lash and three anonymous reviewers for their insightful remarks which helped us improve this work.

REFERENCES

1. Steege AL, Baron SL, Marsh SM, Menéndez CC, Myers JR. Examining occupational health and safety disparities using national data: a cause for continuing concern. *Am J Ind Med*. 2014;57:527–538.
2. Bureau of Labor Statistics, U.S. Department of Labor. Census of fatal occupational injuries: agricultural workers (code 452XXX). Washington, DC: Bureau of Labor Statistics; 2013. Available at: http://data.bls.gov/gqt/InitialPage. Accessed January 29, 2015.
3. Bureau of Labor Statistics, U.S. Department of Labor. Census of nonfatal occupational injuries and illnesses: agricultural workers (code 452000). Washington, DC: Bureau of Labor Statistics; 2013. Available at: http://data.bls.gov/gqt/InitialPage. Accessed January 29, 2015.
4. Peek-Asa C, Sprince NL, Whitten PS, Falb SR, Madsen MD, Zwerling C. Characteristics of crashes with farm equipment that increase potential for injury. *J Rural Health*. 2007;23:339–347.
5. Harland KK, Greenan M, Ramirez M. Not just a rural occurrence: differences in agricultural equipment crash characteristics by rural-urban crash site and proximity to town. *Accid Anal Prev*. 2014;70:8–13.
6. Baker SP, Whitfield RA, O'Neill B. Geographic variations in mortality from motor vehicle crashes. *N Engl J Med*. 1987;316:1384–1387.
7. Muelleman RL, Walker RA, Edney JA. Motor vehicle deaths: a rural epidemic. *J Trauma*. 1993;35:717–719.
8. Muelleman RL, Mueller K. Fatal motor vehicle crashes: variations of crash characteristics within rural regions of different population densities. *J Trauma*. 1996;41:315–320.
9. Zwerling C, Peek-Asa C, Whitten PS, Choi SW, Sprince NL, Jones MP. Fatal motor vehicle crashes in rural and urban areas: decomposing rates into contributing factors. *Inj Prev*. 2005;11:24–28.
10. Iowa Department of Transportation. *Iowa motor vehicle crashes – 1925–2013*. Des Moines, IA: Iowa Department of Transportation; 2014. Available at: http://www.iowadot.gov/mvd/ods/stats/crashhistory.pdf. Accessed January 6, 2015.
11. Illinois Department of Transportation. *Illinois crash data – 2005–2009*. Springfield, IL: Illinois Department of Transportation; 2010. Available at: http://www.idot.illinois.gov/Assets/uploads/files/Transportation-System/Resources/Safety/Crash-Reports/trends/2005–2009%20trends.pdf. Accessed January 6, 2015.
12. Kansas Department of Transportation. *Kansas traffic accident facts: Quick facts*. Topeka, KS: Kansas Department of Transportation; 2005–2008. Available at: https://www.ksdot.org/burtransplan/prodinfo/accista.asp. Accessed January 6, 2015.
13. Minnesota Department of Public Safety. *Minnesota motor vehicle crash facts 2008*. St. Paul, MN: Minnesota Department of Public Safety; 2008. Available at: https://dps.mn.gov/divisions/ots/reports-statistics/Documents/CRASH-FACTS-2008.pdf. Accessed January 6, 2015.
14. Missouri Statewide Traffic Accident Records System (STARS), Missouri State Highway Patrol. *Motor vehicle Traffic Accident Summary: crashes, accident type by accident severity: 1/2005–12/2008*. Jefferson City, MO. Available at: https://www.mshp.dps.missouri.gov/TR10Web/ReportRequest. Accessed January 6, 2015.
15. North Dakota Department of Transportation. *North Dakota crash summary – 2013*. Bismarck, ND: North Dakota Department of Transportation; 2014. Available at: https://www.dot.nd.gov/divisions/safety/docs/crash-summary.pdf. Accessed January 6, 2015.
16. Highway Safety/Accident Records Section, Nebraska Department of Roads. *Traffic crash facts: 2013 annual report*. Lexington, NE: Nebraska Department of Roads; 2014. Available at: http://www.transportation.nebraska.gov/highway-safety/docs/fact-books/facts2013.pdf. Accessed January 6, 2015.
17. South Dakota Department of Public Safety. *2013 South Dakota motor vehicle traffic crash summary*. Pierre, SD: South Dakota Department of Public Safety; 2014. Available at: https://dps.sd.gov/enforcement/accident_records/documents/2013FactsBook.pdf. Accessed January 6, 2015.
18. Wisconsin Department of Transportation. *2011 Wisconsin traffic crash facts*. Madison, WI: Wisconsin Department of Transportation; 2013. Available at: http://www.dot.wisconsin.gov/safety/motorist/crashfacts/docs/crashfacts.pdf. Accessed January 6, 2015.
19. Hughes R, Rodgman E. *Crashes involving farm tractors and other farm vehicles/equipment in North Carolina 1995–1999*. Chapel Hill, NC: Highway Safety Research Center; 2000. Available at: http://www.hsrc.unc.edu/pdf/2000/Farm.pdf. Accessed January 7, 2015.
20. Pinzke S, Lundqvist P. Slow-moving vehicles in Swedish traffic. *J Agric Saf Health*. 2004;10:121–126.
21. Jaarsma CF, De Vries JR. Agricultural vehicles and rural road safety: tackling a persistent problem. *Traffic Inj Prev*. 2014;15:94–101.
22. Gerberich SG, Robertson LS, Gibson RW, Renier C. An epidemiological study of roadway fatalities related to farm vehicles: United States, 1988 to 1993. *J Occup Environ Med*. 1996;38:1135–1140.
23. Wright PH, Robertson LS. Priorities for roadside hazard modification: a study of 300 fatal roadside object crashes. *Traffic Eng*. 1976; 46:24–30.
24. Zador P, Stein H, Hall J, Wright P. Relationship between vertical and horizontal roadway alignments and the incidence of fatal rollover crashes in New Mexico and Georgia. *Transp Res Rec*. 1989; 1111:27–42.
25. Wintemute GJ, Kraus JF, Teret SP, Wright MA. Death resulting from motor vehicle immersions: the nature of the injuries, personal and environmental contributing factors, and potential interventions. *Am J Public Health*. 1990;80:1068–1070.
26. Zador PL, Wright PH, Karpf RS. *Effect of pavement markers on Nighttime crashes in Georgia*. Washington, DC: Insurance Institute of Highway Safety; 1982. Available at: http://www.iihs.org/frontend/iihs/documents/masterfiledocs.ashx?id=660. Accessed November 20, 2014.
27. Vanderbilt T. (ed). *Traffic*. 1st ed. New York, NY: Alfred A. Knopf, Publishers; 2008.
28. Bell N, Schuurman N. GIS and injury prevention and control: history, challenges, and opportunities. *Int J Environ Res Public Health*. 2010;7:1002–1017.
29. US Census Bureau. *Census 2000 TIGER/Line files technical documentation*. Washington, DC: US Census Bureau; 2000. Available at: https://www2.census.gov/geo/tiger/tiger2k/tiger2k.pdf. Accessed January 14, 2015.
30. Clapham C, Nicholson J. (eds). *The Concise Oxford Dictionary of Mathematics*. 4th ed. New York, NY: Oxford University Press Inc.; 2009.
31. Leopold LB, Wolman MG, Miller JP. (eds). *Fluvial Processes in Geomorphology*. 1st ed. San Francisco, CA: W.H. Freeman, Publishers; 1964.
32. Mounib EL, Satchi T. Matched sampling using SAS® software. Boston, MA: Blue Cross Blue Shield of Massachusetts; 2000. Available at: http://www.lexjansen.com/pharmasug/2000/Posters/p07.pdf. Accessed July 25, 2014.
33. Luginbuhl RC, Jones VC, Langley RL. Farmers' perceptions and concerns: the risks of driving farm vehicles on rural roadways in North Carolina. *J Agric Saf Health*. 2003;9:327–348.
34. Costello TM, Schulman MD, Luginbuhl RC. Understanding the public health impacts of farm vehicle public road crashes in North Carolina. *J Agric Saf Health*. 2003;9:19–32.
35. Fitzpatrick CD, Harrington CP, Knodler MA Jr, Romoser MR. The influence of clear zone size and roadside vegetation on driver behavior. *J Safety Res*. 2014;49:97–104.
36. Victor T, Dozza M, Bargam J, et al. Analysis of naturalistic driving study data: Safer glances, driver inattention, and crash risk. Washington, DC: Transportation Safety Research Board; 2015. Available at: http://www.trb.org/Publications/Blurbs/171327.aspx. Accessed October 23, 2015.
37. Great Plains Center for Agricultural Research. *Fall public service announcements: Prevention of farm equipment crashes in Iowa and the Midwest*. Fall 2015. Available at: http://www.public-health.uiowa.edu/gpcah/fall-public-service-announcements/. Accessed October 23, 2015.
38. National Highway Traffic Safety Administration. *Traffic Safety Facts 2013*. Washington, DC: National Highway Traffic Safety Administration; 2015 (#DOT HS 812139). Available at: http://www-nrd.nhtsa.dot.gov/CATS/index.aspx. Accessed October 23, 2015.
39. Lash TL, Fox MP, Fink AK (eds). *Applying Quantitative Bias Analysis to Epidemiologic Data*. New York, NY: Springer Science + Business Media, LLC; 2009.