MOTOR VEHICLE CRASHES AND ADVERSE MATERNAL AND FETAL OUTCOMES AMONG PREGNANT DRIVERS IN NORTH CAROLINA

Catherine Joy Vladutiu

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Approved by:

Dr. Charles Poole

Dr. Stephen W. Marshall

Dr. Carri Casteel

Dr. M. Kathryn Menard

Dr. Harold B. Weiss

ABSTRACT

CATHERINE JOY VLADUTIU: Motor vehicle crashes and adverse maternal and fetal outcomes among pregnant drivers in North Carolina
(Under the direction of Dr. Charles Poole)

Motor vehicle crashes are the leading cause of hospitalized maternal injury morbidity and mortality and traumatic fetal mortality among pregnant women in the United States, yet little is known about their determinants. Ongoing pregnancy-related crash surveillance is lacking and crash-related maternal and fetal outcomes are underreported.

Using linked vital records and crash reports we estimated the risk and examined risk factors for being a pregnant driver in a crash and examined the association between crashes and adverse pregnancy outcomes among 878,546 pregnant North Carolina residents, 16-46 years, who reached the 20th week of pregnancy and delivered a singleton infant between 2001 and 2008. We also examined injury risk factors among pregnant drivers who were in crashes after the 20th week (n=11,052).

The estimated driver crash risk was 12.6 per 1,000 pregnant women. Women who were 18-24 years (vs. 25-34, adjusted risk difference, RD, 0.8, 95% confidence interval, CI, 0.5, 1.1), non-Hispanic black (vs. non-Hispanic white, RD=1.2, 95% CI 0.8, 1.5), unmarried (RD=1.6, 95% CI 1.3, 1.9), or had high school diplomas only (vs. college graduates, RD=1.5, 95% CI 1.1, 1.8) were at higher risk of being pregnant drivers in crashes. The highest rates of preterm birth (adjusted rate ratio, RR, 1.16, 95% CI 0.94, 1.44), stillbirth (RR=4.68, 95% CI 2.77, 7.91), placental abruption (RR=2.20, 95% CI 1.18, 4.09), and premature rupture of the

membranes (RR=1. 48, 95% CI 0.96, 2.27) were observed following pregnant drivers' second or subsequent crashes, compared to no crashes. Pregnant drivers who were unbelted (RD=20.2, 95% CI 12.7, 27.8) or were in crashes severe enough for substantial vehicle damage (RD=18.1, 95% CI 15.9, 20.4) or airbag deployment (RD=27.9, 95% CI 24.8, 31.0) were at greatly increased risk of injury.

Young age, black race, low educational attainment, and unmarried status are associated with an increased risk of being a pregnant driver in a crash. Multiple crashes while driving during pregnancy are associated with elevated rates of adverse pregnancy outcomes. Seat belts reduce the risk of crash-related maternal injury. More research is needed to examine the effect of vehicle safety devices on adverse pregnancy outcomes.

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The results in chapters IV, V, and VI have been or will be submitted for publication in the peer-reviewed literature. Co-authors include committee members listed on the title page.

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LIST OF ABBREVIATIONS

CI	Confidence interval
CODES	Crash Outcome Data Evaluation System
DAG	Directed acyclic graph
DMV	Division of Motor Vehicles
GEE	Generalized estimating equations
HSRC	Highway Safety Research Center
LMP	Last menstrual period
mph	Miles per hour
NC	North Carolina
NH	Non-Hispanic
NNT	Number needed to treat
PROM	Premature rupture of the membranes
Pr	Probability
RD	Risk difference
RR	Rate ratio
SA	Specific aim
SCHS	State Center for Health Statistics
UT	Utah
WA	Washington State

I. STATEMENT OF SPECIFIC AIMS

In the United States, motor vehicle crashes are the leading cause of hospitalized maternal injury morbidity and mortality. It is estimated that 1.3% of pregnant women are involved in crashes annually in the U.S.[1] However, this is likely an underestimate due to difficulties in capturing cases. Ongoing statewide pregnancy-related crash surveillance is lacking and administrative databases are limited, as police-reported crash records lack information on pregnancy status and live birth and fetal death records lack data on crash history. In addition, little is known about the frequency and determinants of crash-related maternal injuries during pregnancy. It is estimated that at least 92,500 pregnant women are injured in crashes each year,[2] but crash-related maternal injuries are underreported. Injury information is often obtained from hospitalization records and only severe injuries are captured, yet pregnant women also sustain minor injuries that may not result in hospitalization.

Motor vehicle crashes not only affect pregnant women, but they can also have devastating effects on the fetus. However, due to the lack of standardized reporting of crash-related fetal injury, little is known about the effect of crashes on fetal morbidity and mortality. A few population-based U.S. studies have examined pregnancy outcomes following crashes.[3-6] While most of these studies focused on the impact of vehicle safety devices[4,6] or maternal injury severity[5] on pregnancy outcomes, only one study compared outcomes for pregnant women in police-reported crashes to those not in crashes.[3] None of these studies described the circumstances surrounding the crash events. To better understand the risk of crashes during pregnancy and the factors that contribute to crash-related maternal and fetal outcomes, more population-based research is needed, particularly in states with relatively high crash risks among pregnant women.

The specific aims of this study were to:

1. Estimate the risk and describe the risk factors for being a pregnant driver in a motor vehicle crash after the 20th week of pregnancy in North Carolina (NC) between 2001 and 2008.
2. Estimate the risk and describe the risk factors for sustaining crash-related maternal injuries among pregnant NC drivers who were in crashes after the 20th week of pregnancy between 2001 and 2008.
3. Examine the association between motor vehicle crashes involving a pregnant NC driver and the rate of preterm birth, stillbirth, placental abruption, and premature rupture of the membranes.

To address aim 1, we examined a cohort of 878,546 pregnant NC residents, aged 16-46 years, who reached the 20th week of pregnancy and delivered a live or stillborn singleton infant in 2001-2008. We used probabilistic record linkage methods to determine whether a crash occurred during pregnancy. Linear risk regression was used to model the overall risk of being a pregnant driver in a crash and to estimate risk differences for selected crash determinants. To address aim 2, we used linear risk regression to estimate risk differences for selected driver, vehicle, and environmental risk factors for crash-related maternal injuries among a cohort of 11,052 pregnant NC drivers who were in crashes after the 20^{th} week of pregnancy. To address aim 3, we used Poisson regression to estimate rate ratios for the association between pregnant driver crashes and adverse pregnancy outcomes among a cohort of 878,546 pregnant NC residents.

This study adds to the small but growing literature on motor vehicle crashes during pregnancy while improving upon existing studies and their research methods. It also increases awareness of this important public health issue and highlights the need for ongoing statewide surveillance to track crashes and injuries during pregnancy. By understanding the risk of pregnancy-related crashes, which factors increase this risk, and what effect crashes have on maternal and fetal outcomes, obstetricians will be able to educate their patients about this important issue and suggest ways to minimize their risk. It will also enable public health professionals to develop more comprehensive strategies for preventing adverse maternal and fetal outcomes from crashes during pregnancy.

II. REVIEW OF THE LITERATURE

Epidemiology of crashes during pregnancy

Motor vehicle crashes during pregnancy are all too common. In the United States, the annual crash rate for pregnant women has been estimated as at least 13 per 1,000 person-years as compared to 26 crashes per 1,000 person-years among non-pregnant women.[1] Although most state-specific crash rates among pregnant women are unknown, there are three states where population-based studies have been conducted to estimate pregnancy crash risks: Pennsylvania, Utah, and Washington State. In Pennsylvania and Utah, the motor vehicle crash risks were 1.1% (between 2002-2005) and 2.8% (between 1992-1999), respectively, among pregnant drivers, with a fairly even distribution of crashes across trimesters.[3,7] In Washington State, the motor vehicle crash risk for pregnant front seat occupants (i.e., drivers and passengers) between 2002 and 2005 was 1.0%, with the majority of crashes occurring during the second trimester.[4] Weiss & Sauber-Schatz[7] suggest that the differences in these statewide crash risks during pregnancy may be due to several state specific factors, including birth rates, the mean maternal age during pregnancy, and the variation of age-specific crash risks for women of reproductive age.

Motor vehicle crashes and maternal outcomes

Motor vehicle crashes are the leading cause of hospitalized injury and injury-related death during pregnancy in the U.S.[8-13] Each year, approximately one million women in the

United States, aged 15 to 44 years, are injured and 6,130 women die as a result of motor vehicle crashes.[14] Although the number of pregnant women injured in motor vehicle crashes in the United States has been estimated to be more than 92,000 annually, this number is likely an underestimate because many crashes are unreported, and pregnancy status may be unknown, especially early in pregnancy.[2] In the United States, the rate of injury from motor vehicle crashes during pregnancy has risen over time. This is mainly a result of increases in exposure—that is, the increasing number of miles driven by pregnant women.[1,15,16] Crashes result in many types of injuries. Minor injuries include dislocations, sprains, contusions, and open wounds.[5] However, more serious adverse outcomes are possible. Blunt and penetrating abdominal trauma from crashes during pregnancy can result in splenic rupture, uterine rupture, pelvic fractures, placental abruption, and maternal death.[5,17-19] The severity of these outcomes depends on a variety of factors, including the gestational age at the time of injury, crash severity, and seat belt use.[3,5,15,19,20]

A handful of population-based studies have been conducted that examined both national and state-specific pregnancy-associated hospitalizations and emergency department visits from trauma during pregnancy.[8-10,12,13,21] Although these studies described maternal injuries and death from all causes during pregnancy, motor vehicle crashes were recognized as the leading cause of maternal injury. In the United States, approximately 26% of injury hospitalizations during pregnancy resulted from motor vehicle crashes.[9] This injury hospitalization risk is similar to the motor vehicle emergency department risks reported in Utah and Massachusetts (22.2% and 27%, respectively) for pregnant women.[8,12] In Washington State, the incidence of pregnancy-associated injury hospitalization was 243.4 per 100,000 live births; motor vehicle crashes were responsible for 30.4% of these injuries.[21] Pennsylvania and California reported lower rates of motor vehicle-related injury hospitalizations among women during pregnancy, with rates of 227 injuries per 100,000 person-years in Pennsylvania and 67 prenatal injuries per 100,000 deliveries and 8 injuries to women at delivery per 100,000 deliveries in California.[10,13]

In addition to the studies that examined injury hospitalizations and hospital emergency department visits from all causes during pregnancy, a few population-based studies[5,7,20,22] focused on adverse maternal outcomes from motor vehicle crashes. In New Mexico, Schiff et al.[20] examined maternal death records between 1986 and 1995 and found that motor vehicle crashes accounted for 70% of all injury-related maternal deaths. Among the women who died, 77% were not wearing seat belts at the time of the crash. A second study conducted by Schiff and Holt[5] in Washington State described the types of injuries sustained by pregnant women who were hospitalized following a motor vehicle crash. Among the 393 pregnant women who sustained crash-related injuries, those who were severely injured (i.e., those with an Injury Severity Score ≥9) were more likely than non-severely injured women to be hospitalized for fractures, dislocations, sprains, intracranial injuries, open wounds, and internal chest injuries.[5] In contrast, a higher percentage of non-severely injured women were hospitalized for contusions.[5] The most recent epidemiological study of motor vehicle crashes during pregnancy found that one third of the 5,929 crashes during pregnancy in Pennsylvania between 2002 and 2005 resulted in minor maternal injuries, 7.5% resulted in more serious injuries, and only 1 resulted in maternal death.[7]

An international population-based study estimated the incidence of maternal injuries and fatalities from motor vehicle crashes in Sweden between 1991 and 2001.[22] Based on a sample of more than one million pregnancies, the incidence rates of maternal injury and death were estimated as 23 per 100,000 pregnancies and 1.4 per 100,000 pregnancies, respectively, which are lower than the overall U.S. and state-specific rates previously reported.[22] However, it must be noted that the overall crash rate in Sweden is lower than the U.S. rate, which may explain the differences observed for pregnant women between the U.S and Swedish studies.[23]

Motor vehicle crashes and fetal outcomes

There is a paucity of information about the effects of crashes on fetal outcomes. Given that approximately 92,500 women are injured from motor vehicle crashes during pregnancy each year,[2] more research is needed to examine the effects of these crashes and subsequent maternal injuries on fetal morbidity and mortality. Injuries during pregnancy not only result in adverse maternal outcomes, but even minor maternal injuries can be life threatening to the fetus. Specifically, traumatic injury during pregnancy, most often as a result of motor vehicle crashes, is an important cause of adverse fetal outcomes.[24] Until birth, the fetus relies on maternal survival and placental circulation for its own survival. After the first trimester, the uterus enlarges while protecting the fetus and providing nutrients, blood, oxygen, and waste exchange. When a mother sustains a traumatic injury, these functions may become impaired and can result in fetal morbidity or death. By the third trimester, pregnant women are at the greatest risk of early labor, placental abruption, amniotic rupture, and fetal-maternal blood transfusion, which can lead to adverse fetal outcomes such as prematurity, low birth weight, fetal distress, and fetal death.[3,5,17,19,21,22] Placental abruption from severe maternal trauma is a leading cause of fetal loss and accounts for a reported 60% to 70% of all fetal injury-related deaths.[25,26] Even in minor or noncatastrophic trauma during pregnancy, the risk to the fetus may be significant. Preterm labor, placental abruption and death can occur among fetuses exposed to minor trauma.

Crash simulation studies

Several simulation studies of automobile crashes during pregnancy have been conducted, primarily at the University of Michigan Transportation Research Institute and the Virginia Polytechnic Institute and State University (Virginia Tech) Center for Injury Biomechanics, with an additional study conducted in Japan. These studies have used female anthropomorphic test devices (i.e. pregnant crash test dummies)[27-31] and computational models[32-38] to better understand the mechanisms of maternal and fetal injuries and death resulting from motor vehicle crashes. More recently, researchers in France have used post mortem human cadavers as an alternative to dummies for a more "realistic" pregnant model to further examine these injury mechanisms.[39,40]

Anthropomorphic devices

Beginning in 1996, Pearlman and Viano developed the first abdominal insert for a female anthropomorphic test device to measure the effect of restraints on abdominal force, fetal head acceleration, and fetal head injury risk across various levels of crash severity, crash speed and restraint position.[28,29] In 2001, modifications were made to improve the size and shape of the pregnant abdomen and to implement instrumentation to better quantify the effect of abdominal forces and fetal accelerations on fetal injury and death.[27] Initial studies using these devices found that high-speed crashes increased abdominal force and fetal head accelerations, primarily with improper seat belt use.[29] In addition, airbag deployment coupled with no restraint use increased the risk of fetal head injury. The combined effect of airbag deployment and shoulder and lap belt use (i.e. 3-point belt) was the most protective for a woman and the fetus.

A recent study of low-impact collisions measured the anterior and posterior abdominal pressure of pregnant dummy models and how it varied by seat belt use and location of impact. It was found that in frontal impact tests, seat belts reduced peak abdominal pressure when contact was made with the steering wheel.[31] In rear impact tests, seat belts reduced secondary contact with the steering wheel.[31] In France, a study by Delotte et al.[39] examined injury mechanisms during crashes using a post mortem human cadaver. This study found that lap belt loading and backrest impact may result in fetal injury. Specifically, the impact of the lap belt on the pelvic bone may lead to fetal head compression and the impact of the backrest may result in increased fetal acceleration.

Computer simulations

Computational models of pregnant occupants in motor vehicle crashes derived from anthropomorphic test devices and human models have been used to investigate the biomechanics of crashes and to assess the effects of crash speed, restraint conditions, and airbag deployment on maternal and fetal outcomes. Computer simulation studies conducted between 2002 and 2008 by Duma et al.,[32-35] Moorcroft et al.,[36,37] and Manoogian et al.[38] were used to predict the risk of adverse fetal outcomes from motor vehicle crashes during pregnancy. Duma et al.[32,33] and Moorcroft et al.[36,37] found that the risk of adverse fetal outcomes and uterine strain increased with crash speed, particularly among unrestrained occupants. Specifically, Duma et al.[32] found that at a speed of 13km/h, the estimated risk of fetal death ranged from 32% for restrained pregnant drivers to 44% for unrestrained pregnant drivers. At a higher speed of 35 km/h (approximately 22 mph), the risks of fetal death increased to 89% and 100%, respectively.[32] Similarly, Moorcroft et al.[37] found that at speeds of 35 km/h, the risk of serious adverse fetal outcomes exceeded 75% among unrestrained pregnant drivers. Moorcroft et al.[36] further noted that uterine strain was a strong predictor of fetal injury, most likely because of placental abruption, with peak uterine strain ranging from 33% among restrained pregnant drivers with airbag deployment to approximately 61% among unrestrained drivers. In regard to maternal outcomes, the risk of abdominal injury and head trauma was the highest among unbelted drivers and lowest among restrained drivers with airbag deployment.[36,37] Overall, in the computer models, 3-point belts in conjunction with airbags were the most effective for preventing maternal injury from motor vehicle crashes during pregnancy.

Case reports

Between 1987 and 2009, there were at least thirty-three published case reports describing maternal and fetal outcomes among 153 pregnant women who were in a motor vehicle crash during their pregnancy (Table 2.1). Among these reports, 139 women sustained injuries and 11 women died as a result of a motor vehicle crash during pregnancy. Adverse fetal outcomes were reported among 133 cases; there were 39 cases of placental abruption, 8 cases of uterine rupture, 6 cases of fetal distress, 23 fetal injuries, 38 fetal deaths and 7 infant deaths. Overall, these reports had several overlapping conclusions. First, fetal injury and death are possible in the absence of maternal injury or in the presence of minor maternal injury during a motor vehicle crash. Second, improper seat belt use may be responsible for adverse maternal and fetal outcomes, including ecchymosis and fetal death. Third, airbag deployment may be a risk factor for uterine rupture, maternal and fetal injury and fetal death.

Table 2.1. Summary of selected case reports involving a pregnant occupant in a motor vehicle crash, 1987-2009

Author, publication year	Location (# of cases)	Belt Status	Airbag Status	Maternal Outcomes	Pregnancy Outcomes
Agran et al., 1987[41]	California (N=9)	unrestrained	unknown	one maternal death, maternal injuries (face, chest, abdomen, head, knee, ribs, ankle)	placental abruption (N=9), low birth weight (N=7), fetal death (N=9, 22-39 wks), skull fracture (N=1)
Chetcuti & Levene, 1987[42]	England (N=1)	restrained	unknown	no maternal injury	placental abruption, bradycardia
Stafford et al., 1988[43]	Ohio (N=8)	restrained (N=2)	unknown	minor maternal injuries	placental abruption (N=8), skull fracture (N=2), fetal death (N=2), infant death (N=2; 1 day)
Evrard et al., 1988[44]	Rhode Island (N=1)	restrained	unknown	internal hemorrhage, rib fracture, pelvic fractures, splenic rupture, maternal death	fetal skull fracture, fetal death
Ford et al., 1989[45]	Australia (N=1)	restrained	unknown	'seat belt' and facial injuries, hemorrhages	fetal death (30 wks)
Landers et al., 1989[46]	Nebraska (N=1)	unknown	unknown	pelvic fracture, uterine laceration	crushed skull, fetal death
Lipton & Thomason, 1994[47]	North Carolina (N=1)	unrestrained	unknown	closed head injury	ectopic tubal pregnancy
van Enk & van Zwam, 1994[48]	Netherlands (N=1)	restrained	unknown	splenic tear	uterine rupture, fetal death (32 wks)
Harrison et al., 1995[49]	Washington (N=1)	restrained	unknown	forehead lacerations, belt abrasions	fetal death (22 wks)
Hartl & Ko, 1996[50]	New York (N=1)	unrestrained	unknown	no maternal injury	placental abruption, fetal skull fracture (41 wks)
Dittrich, 1996[51]	Saudi Arabia (N=1)	unrestrained	unknown	femoral shaft fracture	uterine rupture, fetal death (30 wks)
Rowe et al., 1996[52]	Texas (N=1)	restrained	unknown	unconscious, facial laceration, abdominal ecchymosis	uterine rupture, placental expulsion, decapitated fetus, fetal death (22 wks)
Sims et al., 1996[53]	Pennsylvania (N=3)	restrained	deployed	maternal injuries (face, hand, arms)	All full-term healthy births

Astarita & Feldman, 1997[54]	California (N=1)	restrained	unknown	abdominal pain, vaginal bleeding	uterine rupture, fetal injury (abdomen, liver, kidney, aorta, spine), fetal death (28 wks)
Matthews et al., 1997[55]	Australia (N=1)	restrained	unknown	pelvic fracture	intracranial hemorrhage
Judich et al., 1998[56]	Israel (N=1)	unknown	unknown	chest and abdominal injury, maternal death	uterine lacerations, membrane rupture, amniotic fluid embolism, fetal death (32 wks)
Schultze et al., 1998[57]	Colorado (N=1)	restrained	deployed	no maternal injury	placental abruption, fetal death (28 wks)
Parida et al., 1999[58]	Kentucky (N=2)	restrained	unknown	Case 1: abdominal and thoracic ecchymoses; Case 2: none reported	Case 1: fetal distress, preterm (31 wks), bowel injury, intraventricular hemorrhage; Case 2: preterm (30 wks), low birth weight, bleeding, ecchymoses, intraventricular hemorrhage, renal failure, infant death (5 months)
Bunai et al., 2000[59]	Japan (N=1)	restrained	unknown	no maternal injury	placental abruption, fetal death (24 wks)
Litmanovitz et al., 2000[60]	Israel (N=3)	unknown	unknown	Case 1: no maternal injury; Case 2: injury (face, head); Case 3: facial injury	Case 1: preterm (36 wks), fetal distress; fetal intrathoracic injury; Case 2: preterm (30 wks), fetal distress; Case 3: placental abruption, preterm (29 wks), fetal distress, humerus fracture, lung contusion, hypoxic brain damage
Klinich et al., 2000[61]	Michigan (N=16)	restrained	unknown	maternal injury	unknown
Fusco et al., 2001[62]	New Jersey (N=1)	restrained	deployed	scalp laceration	uterine rupture, fetal skull fracture, fetal death (39 wks)
Weinberg et al., 2001[63]	Scotland (N=1)	restrained	unknown	ankle fracture, subarachnoid hemorrhage, rib fracture, lung contusions, skull fracture, cerebral edema, maternal death	uterine rupture, placental separation, fetal cervical spine fracture, subarachnoid hemorrhage, cord contusion, fetal death (28 wks)
Hnat et al., 2003[64]	Ohio (N=1)	unknown	unknown	closed head injury, liver lacerations, comatose (240 days)	healthy infant born at 37 weeks
Alley et al., 2003[65]	Kansas (N=1)	unrestrained	unknown	forehead abrasion, respiratory distress, spleen laceration	placental abruption, preterm (28 wks), low birth weight, cerebral edema, infant

					death (20 hours)
Rainio & Penttila, 2003[66]	Finland (N=1)	restrained	un-equipped	maternal injury (ribs, liver), death	amniotic fluid embolism, full-term birth (38 wks), brain damage, pneumonia, infant death
Hagmann et al., 2004[67]	Switzerland (N=1)	unrestrained	unknown	closed femur fracture	preterm (30 wks), intracranial injuries
Karimi et al., 2004[68]	Texas (N=1)	restrained	deployed	abdominal bruising	membrane rupture, preterm (29 wks), hypotension, respiratory failure, brain injury, infant death
Kiryabwire et al., 2005[69]	Australia (N=1)	restrained	unknown	seat belt marks on the abdomen	placental abruption, fetal distress, subarachnoid hemorrhage, preterm (34 wks)
Metz & Abbott, 2006[70]	Colorado (N=30)	unrestrained (N=15)	deployed	Closed head injury (N=2), abrasions (N=5), fractures (N=4), neck strain (N=3), no injuries (N=17), abdominal contusions (N=2)	Placental abruption (N=1), bleeding (N=2), fetal death (N=1 at 28 wks)
Weir et al., 2008[71]	Texas (N=1)	restrained	un-equipped	abdominal ecchymosis	Uterine rupture, fetal death (22 wks)
Klinich et al., 2008[72]	Michigan (N=57)	unrestrained (N=10)		Maternal injuries: none (N=8), minor (N=29), moderate (N=11), major (N=9). Fatalities: (N=6)	Placental abruption (N= 12), Fetal death (24-36+ wks) (N=12), preterm (N=6), fetal head injury (N=3), fetal distress, intraventricular hemorrhage
Nguyen et al., 2009[73]	California (N=1)	restrained	deployed	bruising (neck, abdomen)	Preterm (26 wks), skull fracture, infant death

Population-based studies

Only a few population-based studies have examined the association between motor vehicle crashes and fetal outcomes.[3-6,22] Overall, findings from five epidemiological studies suggest that pregnant women are at increased risk of experiencing several adverse fetal outcomes after a motor vehicle crash, particularly low birth weight, preterm delivery, and fetal death (Table 2.2).

In Washington State, Wolf et al.[6] examined the effect of motor vehicle crashes and seat belt use on pregnancy outcomes and found that unbelted pregnant women in a crash had almost twice the risk of having a low-birth-weight baby and 4 times the risk of losing their fetus than belted women. A more recent study in Washington by Schiff & Holt[5] found that pregnant women hospitalized following a crash had a 40% higher risk of having a preterm baby than those not in a crash. This risk increased to 60% for women who were severely injured in the crash. A third study conducted in Washington State, between 2002 and 2005, examined the subset of pregnant women who were drivers or occupants in the front seat in a crash.[4] This study found that pregnant women in a crash with an airbag available had a 10% higher risk of having a preterm or low-birth-weight baby than pregnant women whose car did not have an airbag. These findings differed when assessing airbag deployment. Pregnant women who were in a crash with a deployed airbag had a 20% lower risk of having a preterm or low-birth-weight baby compared with those in a crash without a deployed airbag.[4] In Sweden, pregnant women in a crash had almost four times the risk of losing their fetus compared with women not in a crash during pregnancy.[22] Although these four studies provide important information regarding the risk of fetal outcomes from motor vehicle crashes, one study[5] focused on women assessed after the crash using hospital discharge data and only captured the most severe crashes, and two studies[4,6] only focused on pregnant women who were in a crash without including a non-crash comparison group.

Given that minor injuries can significantly affect the well-being and survival of a fetus, it is important to examine the effect of all reported motor vehicle crashes on fetal outcomes, including those that did not result in hospitalization. Data regarding the impact of non-hospitalized crashes on fetal outcomes are lacking. Only one published U.S. study has examined the effect of motor vehicle crashes using non-hospitalized crash data while also including a non-crash comparison group by linking police-reported motor vehicle crashes and vital records in Utah between 1992 and 1999.[3] This study found that, overall, pregnant women in a crash were not at higher risk of adverse birth outcomes than pregnant women not in a crash. However, when examined by belt status, unbelted pregnant women in a crash had a 30% higher risk of having a low-birth-weight baby compared with pregnant women not in a crash and almost three times the risk of a fetal death as belted pregnant women.[3] Although this is the only study that has linked statewide databases to explore fetal outcomes resulting from hospitalized and non-hospitalized crash victims, there are several limitations that must be addressed in future research to better assess this important public health issue. Specifically, there was no vehicle deformity information to adequately assess crash severity; there were not enough outcomes to assess interactions with gestational age; the study population was relatively small; and the study did not account for gestational age at the time of crash in relation to delivery or death. More research is needed to build on the Utah study to quantify the impact of motor vehicle crashes on fetal outcomes.

Table 2.2. Summary of findings from five population-based studies that assessed the effect of motor vehicle crashes during pregnancy on fetal outcomes, 1993-2010.

Author, publication year	Location, sample size	Study Population[a]	Adjusted[b] and Unadjusted Risk Ratio Estimates							
1. Hyde et al., 2003[3]	Utah, N=322,704	All pregnant women	Crash vs. no crash		Belted vs. no crash		Unbelted vs. no crash		Unbelted vs. belted	
Preterm birth			1.02	0.94, 1.11	1.08	0.99, 1.18	1.13	0.91, 1.40	1.00	0.78, 1.29
Low birth weight			1.03	0.94, 1.14	1.06	0.95, 1.18	1.30	1.03, 1.64	1.18	0.89, 1.56
Fetal death			--	--	--	--	--	--	2.80	1.40, 5.60
2. Kvarnstrand et al., 2008[22]	Sweden, N=1,094,559	All pregnant women	Crash vs. no crash							
Fetal death			3.55	2.43, 5.20						
3. Schiff and Holt, 2005[5]	Washington, N=17,889	All pregnant women hospitalized for crashes and a random sample of pregnant women not hospitalized for crash-related injuries	Crash vs. no crash		Severely injured vs. no crash		Non-severely injured vs. no crash		Uninjured vs. no crash	
Preterm birth			1.40	1.10, 1.90	1.60	0.80, 3.10	1.10	0.80, 1.80	1.60	1.00, 2.60
Low birth weight			--	--	1.40	0.60, 3.20	1.10	0.60, 1.80	1.80	1.00, 3.10
Fetal death			--	--	9.00	2.10, 37.10	1.30	0.20, 9.80	--	--
4. Schiff et al., 2010[4]	Washington, N=3,348	All pregnant women in motor vehicle crashes			Airbag available vs. airbag not available		Airbag deployed vs. airbag not deployed			
Preterm birth					1.10	0.80, 1.60	0.80	0.30, 1.90		
Low birth weight					1.10	0.70, 1.60	0.80	0.30, 2.00		

Fetal death			--	--	--	--		
5. Wolf et al.,1993[6]	Washington, N=2,592	All pregnant women in motor vehicle crashes					Unbelted vs. belted	
Low birth weight							1.90	1.20, 2.90
Fetal death							4.10	0.80, 20.30

[a]Schiff and Holt linked vital records to hospital discharge data, whereas the other 4 studies linked vital records to motor vehicle crash reports.

[b]Hyde et al. adjusted for maternal age, tobacco and alcohol use, race, education, parity, prenatal care, and weight gain; Kvarnstrand et al. did not adjust for covariates; Schiff and Holt adjusted for maternal age and tobacco use with the exception of the unadjusted relative risk estimate for fetal death comparing severely injured women to those not in a crash; Schiff et al. adjusted for maternal age, seat belt use, and vehicle model year; Wolf et al. adjusted for maternal age and gestational age at crash.

Seat belt studies

Seat belts are known to reduce occupant injury and death during crashes. Among pregnant women, studies have shown that seat belts are effective at reducing the risk of adverse maternal and fetal outcomes.[3,6,72] However, these studies did not have data regarding how seat belts were worn and how proper or improper use may affect the risk of these outcomes. Police reported crash records across all states lack information on proper seat belt use during pregnancy. The American College of Obstetricians and Gynecologists recommends that during pregnancy, women should wear seat belts properly by wearing a 3-point restraint, with the lap belt placed below the abdomen and the shoulder belt placed diagonally above the abdomen.[74] Lap or shoulder restraints alone are not suitable. As suggested in the computational models and case reports, improper restraints can result in increased risk of uterine rupture or abdominal injuries that may further result in excessive maternal bleeding and/or fetal death. A recent case series of 57 pregnant women found that improperly restrained occupants had a higher risk of adverse fetal outcomes than properly restrained occupants.[72] Using a risk curve estimated from crashes at a speed of 30 km/h, this study further estimated that there would be an 84% reduction in the risk of adverse fetal outcomes if women were properly restrained.[72]

Airbag studies

Similar to seat belts, airbags were first developed as safety devices to reduce injury and death among occupants of motor vehicles during crashes. Although the benefits of airbags have been shown among non-pregnant populations, not much is known about the beneficial effect of airbags during pregnancy. In addition, it is unknown if airbags cause injuries during pregnancy since pregnant women may be unable to maintain the National Highway Traffic Safety Administration's recommended 10-inch distance between themselves and the airbag, particularly during later stages of pregnancy. A review of three case reports in Pennsylvania suggested that airbags in combination with seat belts do not increase the risk of injuries.[53] In contrast, the findings from several other case reports have suggested that airbag deployment without seatbelt use may result in maternal and/or fetal injury or death.[57,62,68,70,73] However, population-based studies are lacking. Only one state-based study has examined the effect of airbags on maternal and fetal outcomes.[4] This study found that airbag deployment did not increase the risk of several adverse fetal outcomes in crashes during pregnancy in Washington State. Given the mixed findings from the published case reports and the population-based study, more research is needed to quantify the effect of airbags on maternal and fetal morbidity and mortality. As a passive vehicle safety device, airbags require no behavioral adherence from drivers and passengers, and if effective, they can be important safety devices for preventing adverse outcomes from motor vehicle crashes during pregnancy, particularly in conjunction with 3-point restraints.

Motor vehicle safety interventions

Seat belt practices

Given the evidence suggesting the benefits of seat belt use during pregnancy, it is important that all pregnant women wear belts and wear them properly while in a motor vehicle. In the United States, an estimated 84.1% of pregnant women (compared to 83.8%

of all reproductive-age women) report wearing seat belts.[75] Several state-specific studies have been conducted to assess pregnant women's beliefs and practices regarding seat belt use.[2,75-81] Most studies found that although pregnant women report wearing belts, very few wear them properly. Women who refrain from wearing seat belts during pregnancy report that they find them uncomfortable or fear that they will cause injury to themselves or their fetus. For example, a study conducted in the early 1990s found that among 298 pregnant women in Michigan, 78% reported belt use during pregnancy.[76] Among those who reported that they rarely or never use a seat belt, almost half reported that the belt was uncomfortable, 29% never used seat belts by habit, and 16% feared hurting their fetus.[76] In regard to proper belt use, at the first prenatal visit only 53% reported proper belt use, whereas 68% reported proper placement when asked at the third trimester visit.[76]

Another study conducted in the late 1990s assessed restraint use among 807 pregnant women in California.[80] This study found that although most women (86%) reported restraint use during pregnancy, only half wore them properly. In addition, 9% believed that seat belts were harmful to their fetus.[80] A third study conducted in 2001 among pregnant patients receiving care from 1 of 8 health centers in Jefferson County, Alabama, estimated a higher prevalence of reported belt use than was estimated in other studies.[78] Approximately 96% of pregnant women reported that they wear seat belts, and 72% reported that they use belts properly.[78] Among the women who did not always wear their seat belt, the most common reasons for underuse included discomfort (53%), forgetting to wear belts (43%), or belief that belt use was not necessary (19%).[78] Other explanations for lack of belt use included inconvenience (12%), fear of injury to the fetus

(12%), and fear of injury to themselves (4%).[78] A second phase of this study assessed differences in restraint use and knowledge between county clinic patients and private practice patients.[79] The authors found that a higher proportion of private practice patients used belts before and during pregnancy and used them correctly as compared with county clinic patients.

An Irish study assessed frequency and awareness of proper belt use among pregnant women in Northern Ireland between 2003 and 2004.[77] Similar to the results from the U.S.-based studies, approximately 75% of the 154 respondents reported belt use during pregnancy while driving, and 47% reported proper belt use. One third of the women reported concerns about wearing a seat belt during pregnancy, and only 22% reported that they received belt use advice during pregnancy.

Although the reported prevalence estimates of seat belt use across several studies indicate that most pregnant women (i.e., 75% to 96%) wear seat belts during pregnancy, not all of these women (i.e., 47% to 76%) wear belts properly. In addition, among the pregnant women who reported that they rarely or never use a seat belt, a small percentage had misconceptions about the effects of belt use on themselves and their fetus. Proper education about the importance of belts and correct placement can minimize concerns and correct misconceptions that prevent women from wearing belts and can increase proper belt use. An evaluation of an educational intervention disseminated in prenatal care clinics in Alabama found that providing women with educational materials that address the importance and proper use of seat belts resulted in increased knowledge of belt effectiveness for pregnant women and fetuses, increased belt use, and increased proper placement of lap and shoulder belts.[82] Earlier studies evaluating the effectiveness of educational interventions in childbirth classes and in obstetric clinics had similar findings.[80,83] One intervention resulted in increased frequency of seat belt use,[83] and the other resulted in improved belt placement.[80]

As recommended by the American College of Obstetricians and Gynecologists, all pregnant women should receive prenatal seat belt counseling.[74] However, this is usually not the case. Very few pregnant women report that they received prenatal counseling about belt use.[2,75,76,78,80] A multistate study conducted across 22 states found that the prevalence of reported prenatal counseling about belt use ranged from 38% (Arkansas) to 59% (Washington State).[2] This range is consistent with the findings from several prenatal clinic-based studies. For example, in Michigan, approximately 55% of women who completed a survey at two prenatal visits (n=298) reported that they received information about belt use from their health care provider.[76] In Alabama, only 37% of the 450 women who completed surveys at their prenatal visits reported that they received information on belt use during pregnancy.[78] In California, even fewer women (21%) reported that they received information on proper belt use from their health care provider.[80]

Additional Safety Interventions

Although existing motor vehicle safety devices, such as seat belts and airbags, probably provide increased protection for pregnant women and their fetuses in regard to adverse outcomes compared to no devices, more safety interventions are needed, particularly those targeted toward vehicle design, legislation development, and behavior modification.

Vehicle design

Existing vehicle crash protection systems can be improved for pregnant women and fetuses. The performance standards for vehicle safety designs are based on the stature and anatomy of average male drivers. As such, pregnant women may be uncomfortable with the positioning of certain vehicle devices (e.g., belts and steering wheels) and may subsequently adjust these devices, thus putting themselves and their fetus at risk of injury. Therefore, automobile manufacturers should consider pregnant women when designing and testing vehicles and their safety devices in order to better accommodate the size and shape of these women.

In addition to changes in vehicle design, protective devices worn in the vehicle may theoretically prevent injuries to pregnant women in crashes. For example, developers in Columbus, Ohio recently designed non-metal pregnancy "shields" of various sizes that could be fit over a pregnant woman's abdomen while sitting in the vehicle.[84] The purpose of the shield is to redistribute forces, prevent seat belt intrusion, and reduce placental abruption in a crash during pregnancy. However, this and other related devices have not been studied for effectiveness.

Legislation

Although prior studies indicate that an estimated 75% to 96% of pregnant women report wearing seat belts, there are pregnant women who rarely or never wear belts. Legislative efforts to improve motor vehicle safety during pregnancy, such as primary seat belt laws, can help to ensure that pregnant women, like all occupants, are wearing their seat belts during pregnancy. In the general population, evidence from the 2009 National Occupant Protection Usage Survey shows that belt use in states with primary belt enforcement laws (88%) is higher than belt use in states without primary belt enforcement laws (77%).[85] Therefore, enforcement of mandatory belt laws and adoption of primary seat belt laws may encourage pregnant women to wear seat belts at all times.

Behavior modification

There are several behavioral interventions that can be implemented to improve motor vehicle safety during pregnancy. For example, effective programs are needed to improve proper seat belt use. Educational interventions that emphasize the importance of correct belt placement can increase the use and proper placement of seat belts during pregnancy.[80,82,83] In addition, pregnant women can be encouraged to decrease their crash risk by modifying their driving behaviors and driving use. Although not much is known about the circumstances surrounding crash events among pregnant women, ambient light, weather conditions, types of roadways, and vehicle speed are known to contribute to motor vehicle crash risks in the general population.[86,87] As such, pregnant women could consider doing most of their driving when safe conditions prevail—that is, during the day, in good weather conditions, on well-maintained roads, and at average speeds in order to minimize their crash risk. Alternatively, some women may choose to reduce their driving frequency and distances during pregnancy (i.e., lowering exposure) to avoid the potential for crash involvement.

Conclusion

Although many pregnant women and their fetuses are injured in motor vehicle crashes each year in the United States, population-based research pertaining to the effect of crashes on maternal and fetal outcomes and interventions aimed towards the reduction of crashes and improved safety during pregnancy are limited. To date, only five population-based studies have examined the association between motor vehicle crashes and maternal and fetal outcomes;[3-6,22] none of these studies described the circumstances surrounding the crash events. In addition, only two population-based studies[3,6] have assessed the effect of seat belts, and one population-based study[4] examined the effect of airbags on maternal and fetal outcomes from crashes during pregnancy. More research is needed to better understand the circumstances surrounding crash events and the factors that contribute to crash-related maternal and fetal injuries. To facilitate this research, states should adapt pregnancy-related crash surveillance systems by utilizing probabilistic record linkage methodology of existing records (i.e., vital records and motor vehicle crash records) to track and monitor motor vehicle crashes during pregnancy. Currently, this information is not routinely collected in most states, yet all states collect vital records and crash data. To date, studies using probabilistic record linkage to examine crashes during pregnancy have only been conducted in four states (North Carolina, Pennsylvania, Utah, and Washington). Collective efforts to improve surveillance systems and conduct epidemiological research can help identify pregnancy-related risk factors for maternal and fetal injuries from crashes, which will aid in developing and implementing the most effective interventions.

Evidence-based interventions are needed to reduce the frequency of crashes and to minimize the risk and severity of crash-related injuries through increased seat belt use and proper placement of belts among pregnant women and the development of novel vehicle safety devices. Although there are no published studies pertaining to interventions to reduce driving frequency or modify high-risk driving behaviors among pregnant women, there are evidence-based studies regarding the effectiveness of educational interventions to increase belt use and proper placement of belts.[80,82,83] Evaluations of these interventions have shown that providing pregnant women with prenatal seat belt counseling and/or educational materials is effective at increasing their knowledge of the effectiveness, use, and placement of belts. Therefore, existing interventions for belt use should be more widely implemented, and new interventions focused on other high-risk driving behaviors should be developed and evaluated. In addition, the development and evaluation of personal safety devices, such as the pregnancy shield,[84] may provide another avenue for increased protection against adverse maternal and fetal outcomes from crashes during pregnancy.

III. RESEARCH DESIGN & STUDY METHODS

Overview

This retrospective cohort study included three components: 1) linear risk regression to estimate the risk of being a pregnant driver in a crash after the 20th week of pregnancy and to estimate risk differences for crash determinants using linked vital records and crash reports for 878,546 pregnant NC residents, aged 16-46 years, between 2001-2008 (Specific Aim 1); 2) linear risk regression to estimate the risk of being injured in a crash and to estimate risk differences for injury risk factors using linked vital records and crash reports for 11,052 pregnant NC drivers who were in crashes after the 20th week of pregnancy (Specific Aim 2); 3) Poisson regression to estimate rate ratios for the association between crashes and adverse pregnancy outcomes using linked vital records and crash reports for 878,546 pregnant NC residents, aged 16-46 years, who completed a total of 115,797,259 pregnancy days after the 20th week (Specific Aim 3). Methods common to all components are described, followed by methods specific to each component. This study was approved by the Institutional Review Board of the University of North Carolina at Chapel Hill.

Data sources

North Carolina live birth and fetal death records

Live birth and fetal death certificates were obtained from the NC State Center for Health Statistics (SCHS). These certificates are completed by hospital administrators and verified by physicians within 5-10 days of birth or death. Available birth certificates exclude special registrations (i.e. adoptions, witness protection) and available fetal death certificates exclude induced abortions and fetal deaths occurring before 20 weeks. Medical examiners certify the cause of most deaths (e.g., deaths resulting from injury, suicide, or homicide) while physicians determine the cause of death for non-medical examiner deaths. All reports are sent to the county registrar to be checked for accuracy and completeness and further information is requested if necessary. Certificates are then sent to the Department of Health and Human Services for report processing, corrections, and data entry.

A data request for identifiable live birth and fetal death records between 2001 and 2008 was approved on March 16, 2009 by Thomas Reeher, Interim State Registrar and Director of Vital Records at the NCSCHS. All approved data records (n=993,274) were provided on a compact disc by Matt Avery, Vital Statistics Supervisor, at the NCSCHS.

North Carolina police-reported motor vehicle crash reports

North Carolina has comprehensive motor vehicle crash data that provide detailed information on driver, vehicle, and environmental characteristics. The crash data are reported by law enforcement officers using the Division of Motor Vehicles (DMV) Form 349 and are available from the NC Department of Transportation's DMV. This form is only completed for police-reported motor vehicle crashes that occurred on public roadways and resulted in a fatality or non-fatal personal injury to any vehicle occupant, total property damage greater than $1000, or property damage of any amount to a vehicle seized. The DMV-349 form aids police officers in a thorough examination of all elements contributing to the crash.[88] Within ten days of the crash investigation, all reports are provided to the DMV and staff members enter the reports into an electronic database.

A data use agreement for identifiable police-reported crash records between 2001 and 2008 was approved on May 19, 2009 by David Harkey, Director of the University of North Carolina Highway Safety Research Center (HSRC). Crash reports were linked to driver's license records to obtain the driver's first, middle, and last name and residential address (98.7% linked). All approved data records (n=2,058,918) were provided on a compact disc by Eric Rodgman, Senior Database Analyst, at the HSRC.

Probabilistic record linkage

Overview

Record linkage is a method that is frequently used in epidemiological studies to obtain a comprehensive dataset by combining information for individuals or events from two or more data sources. There are two types of record linkage approaches that are commonly used, including deterministic and probabilistic linkages. The deterministic approach links a pair of records by comparing variables (i.e., fields) common to the records and ensuring that they are an exact match (i.e., one-to-one matching). Alternatively, the probabilistic approach links a pair of records by using the statistical properties of fields common to the records to calculate probabilities that they refer to the same individual or event. Although both approaches are able to identify exact matches, only the probabilistic approach can quantify the strength of the matches through the estimation of match probabilities.

For this study, we used probabilistic record linkage to determine whether a motor vehicle crash occurred during pregnancy in NC by linking individual vital records for singleton deliveries among mothers aged 16-46 years (n=952,602) to state crash records for licensed female drivers aged 16-46 years (n=991,589). This linkage was performed using LinkSolv generalized linkage software (Strategic Matching Inc., Morrisonville, NY, 2009).

Probabilistic record linkage theory

The probabilistic record linkage methodology used in this study is based on the Fellegi-Sunter model[89] which extends an earlier model developed by Newcombe and Kennedy.[90,91] This method uses an optimal decision approach to classify record pairs as matches or non-matches by computing a cutoff threshold weight from match and non-match probabilities.[89] More specifically, probabilities of agreement (i.e., *m* and *1-m* probabilities) and disagreement (i.e., *u and 1-u* probabilities) are estimated for fields that are common to a pair of records. The *m* probability is the probability that a field agrees given that the pair of records is a true match (i.e., one minus the error rate of the field); the *u* probability is the probability that a field agrees given that the pair of records is not a true match (i.e., probability that the agreement occurred by chance).[92-94]

Fields can vary in their ability to provide sufficient information for identifying a true match; they can also have different error rates. Thus, match weights are used to account for these variations by measuring each field's contribution to the overall match probability.[94,95] Based on the Fellegi-Sunter model,[89] weights are estimated as log likelihood ratios of the agreement and disagreement probabilities for each field (i.e., log odds of a match) and are computed as: $\log_2 (m/u)$ if the field agrees for a record pair; and $\log_2 (1\text{-}m/1\text{-}u)$ if the field disagrees for a record pair. Separate weights are calculated for each data value of a field. This approach assumes independence between the *m* probabilities and between the *u* probabilities. Data values from one field should not depend on the data values from another field and data errors (e.g., miscoded fields or misspelled words) should be uncorrelated.[92] Weights can be adjusted to account for these dependencies.

Following the derivation of individual weights, composite match weights are computed for each record pair by summing the individual weights for all field comparisons.[94,95] A cutoff weight is computed based on the size of the data files, the expected number of matches, and the desired minimum probability of a true match.[94] Linked record pairs are ranked in order of their match weights from highest to lowest and those with a match weight that is greater than the cutoff weight are classified as matches; all other record pairs are classified as non-matches. Alternatively, two cutoff values can be estimated to classify record pairs into three categories: matches, possible matches, and non-matches. This latter approach requires manual review of possible matches to determine if the record pairs are matches or non-matches.

Application of record linkage to our cohort study

Data processing

In this study, there were several steps for conducting the probabilistic record linkage. These steps were grouped into three phases, including the pre-linkage, linkage, and post-linkage phases (Figure 3.1). In the pre-linkage phase, we cleaned and standardized data values within each dataset to ensure that common fields had similar definitions and formats. For example, we reformatted date fields (e.g., MMDDYY8.), converted numeric values to characters, compressed hyphenated fields (e.g., last names), and truncated numeric strings (e.g., zip codes). We also examined missing and implausible values. Missing values were converted to null values.

Although there were two datasets included in this study, we had to select error probabilities from one dataset in order to estimate the agreement and disagreement weights. We selected error probabilities from vital records data since they provided a better representation of our cohort of pregnant women. Error probabilities were manually updated for all fields to reflect those that were observed in a preliminary linkage of the 2001 NC vital records and crash data. Table 3.1 summarizes the fields that were obtained from the vital records data.

Figure 3.1. Probabilistic record linkage process

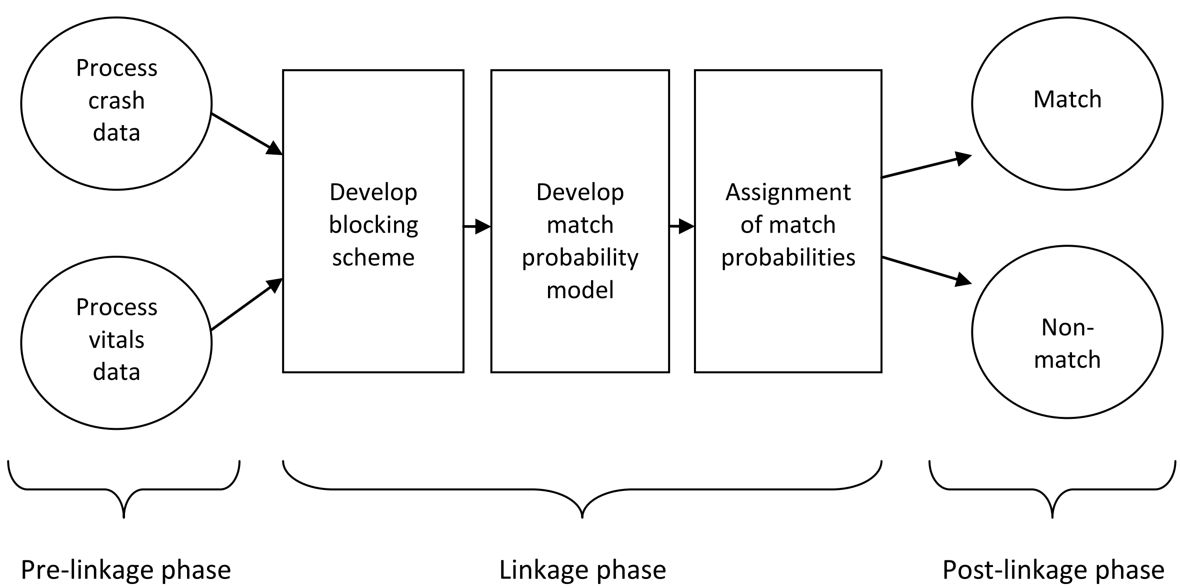


Table 3.1. Summary of vital records data fields considered for the record linkage

Field Name	Info[a]	Modal Value[b]	Frequency[c]	Pr Mode[d]	Pr Miss[e]	Pr Error[f]
Mother's date of birth	13.2	01/01/1980	219	0.00023	0.000	0.030
Mother's date of birth (month, day)	8.5	01/01	3303	0.00347	0.000	0.030
Mother's age	4.6	24	52545	0.05516	0.000	0.030
Child's date of birth	11.5	09/14/2007	480	0.00050	0.000	0.000
First name	10.6	Jennifer	23370	0.02453	0.000	0.060
First initial	4.1	A	106792	0.11211	0.000	0.060
First soundex[g]	8.1	M600	28677	0.03011	0.000	0.060
Middle name	9.2	Marie	50250	0.06071	0.131	0.200
Middle initial	3.8	L	143799	0.17373	0.131	0.200
Middle soundex[g]	7.0	L500	59567	0.07196	0.131	0.200
Last name	13.5	Smith	10436	0.01096	0.000	0.050
Last initial	4.2	M	93964	0.09869	0.000	0.050
Last soundex[g]	10.0	S530	11055	0.01161	0.000	0.050
Zip code	8.8	28540	8060	0.00852	0.007	0.050
Residential county	5.6	060	102429	0.10784	0.003	0.090
Mother's race	1.1	1	690155	0.72470	0.000	0.030

Abbreviations: Pr, probability
[a] Measure of the field's ability to identify a true match
[b,c] Most common data value (i.e., modal value) and its relative frequency
[d] Probability of observing the modal value
[e] Probability of missing data values within the field
[f] Probability of erroneous data values within the field (i.e., probability of disagreement given two records match)
[g] Soundex is a phonetic algorithm for indexing names by sound (i.e., first letter of the name followed by 3 numeric digits)[3]

Blocking field selection

In the linkage phase, we specified blocking fields across both datasets. Since the datasets for the record linkage were large and contained up to 9.4×10^{11} record pairs for comparison, blocking strategies were used to limit the number of comparisons by reducing the number of record pairs that were likely to be non-matches. In general, blocking is the process of partitioning data files into smaller subsets that match on a pre-specified field or group of fields (i.e., blocking field).[92,95] Records included in these subsets must agree on the blocking field. In this study, we chose three pairs of blocking fields, including: 1) mother's date of birth (i.e., full date) and county of residence; 2) mother's date of birth (i.e., month, day) and mother's last name (i.e., soundex); and 3) mother's first name and county of residence. We selected these pairs of blocking fields because they had low error probabilities (i.e., high weights) and could provide a substantial amount of information for identifying a true match. Since a record pair that disagreed on a particular block would automatically be considered a non-match, we chose more than one pair of blocking fields. Three record blocking passes were selected to allow a record pair to rematch on a subsequent block if it did not agree on the blocking requirements for other passes. Multiple passes minimized the occurrence of false non-matches.

Matching field selection

In addition to selecting blocking fields, we chose match fields to compare across record pairs within the same block, including: mother's date of birth; mother's first, middle, and last names; residential county; mother's race; and date of the events (i.e., crash and birth). To account for erroneous data values and differences in data collection methods, we quantified how much the data values for the matching fields were allowed to differ (i.e., tolerance) for record pairs to be considered a match. In order to receive an agreement weight, the following conditions were required for each record pair: mother's date of birth, middle initial, residential county, or race had to match exactly; child's date of birth had to occur within 300 days after the crash date; mother's age had to match within 2 years; and up to 30% of the prefix for the mother's first or last name was allowed to differ (Table 3.2).

In this linkage, we controlled for dependencies between the match fields by multiplying match weights by an agreement or disagreement factor (Table 3.2). For example, the agreement and disagreement for mother's age and for the month and day of birth depend on the mother's date of birth being coded correctly. If this date was recorded incorrectly, then mother's age, month and day of birth would also be incorrect. Therefore, we adjusted the disagreement weight for mother's date of birth by a factor of 0.91 to account for possible recording errors in this field. We also adjusted the agreement weights for child's date of birth (i.e., month, day), mother's age, first name, and last name. All agreement and disagreement factors were obtained from the outcome tests conducted on a preliminary linkage of the 2001 NC vital records and crash data.

Table 3.2. Summary of match field specifications for comparing vital records and crash data

Match Field Name (for vital records and crash data)	Compare Method[a]	Tolerance (range)[b]	Pr Differ[c]	Agree factor[d]	Disagree factor[e]
Mother's date of birth (month, day)	Exact	0,0	0.000	0.99	0.91
Age	Number	-2,2	0.000	0.99	0.91
Child's date of birth (vs. crash date)	Days	0,300	0.001	1.00	1.00
First name	PrefixPct	0,30	0.000	0.98	1.00
Middle initial	Exact	0,0	0.000	1.00	1.00
Last name	PrefixPct	0,30	0.000	0.98	1.00
Residential county	Exact	0,0	0.000	1.00	1.00
Mother's race	Exact	0,0	0.000	1.00	1.00

Abbreviations: Pr, probability
[a] Method of comparison for match fields
[b] Range of error tolerated within the data values of a match field
[c] Probability that data values will differ given that they are coded correctly
[d] Agreement adjustment for match weights to account for dependencies
[e] Disagreement adjustment for match weights to account for dependencies

Assignment of match probabilities

In the final steps of the linkage, we estimated match probabilities and weights in order to classify record pairs as matches or non-matches. We estimated *m* probabilities for each field by subtracting the estimated error rates from 1. These error rates were based on a preliminary linkage of the 2001 NC vital records and crash data. Fields with data values that were allowed to differ (e.g., mother's age, child's date of birth, mother's first and last name) were more likely to agree than those that had to match exactly (e.g., mother's date of birth, middle initial, county, and race). The *u* probabilities were computed by the software which multiplied the relative frequency of each field's data values across both datasets. Frequent values resulted in higher *u* probabilities while less frequent values resulted in lower *u* probabilities. For each field, individual weights were estimated as log likelihood ratios of the agreement and disagreement probabilities while adjusting for dependencies. These weights were summed to compute composite match weights for each record pair.

In order to classify a linked pair as matched or unmatched, we compared the composite match weights for each record pair (i.e., log odds) to a cutoff weight of 21.69. Linked record pairs were ranked from highest to lowest based on their match weights and probabilities. Since we specified a false positive rate of 0.01 for the linkage, linked record pairs were selected one-by-one until the total number of records divided by the sum of (1-match probabilities) was equivalent to 0.01 (or 1%). There were 103,713 linked vital records and crash reports.

Post-linkage assessment

After the linkage was completed, we determined if the crash occurred during pregnancy by comparing the date of the last menstrual period (LMP) to the date of the crash to ensure that no more than the total number of weeks of gestational age at delivery elapsed between the date of LMP and the crash event. If the date of LMP was missing or provided an implausible gestational age based on weeks of gestation and birth weight, the clinical estimate of gestational age was used (n=51,593 or 5.2%). If the date of LMP and the clinical estimate of gestational age were both missing, the physician's estimate of gestational age (i.e., gestational age estimated from pregnancy history, early ultrasound, or examination of the stillborn infant), if known, was used, but only for fetal deaths (n=531, <0.1%). If all values were missing, then gestational age was considered missing and crash involvement could not be determined (n=481, <0.1%). There were 26,913 linked vital records and crash reports for drivers who were pregnant at the time of the crash.

Measures

Motor vehicle crashes and crash severity

A motor vehicle crash was defined as a police-reported crash that involved a licensed female who was the driver of a motor vehicle or passenger truck. Crash reports were only completed if the crash occurred on a public roadway and resulted in a fatality or non-fatal personal injury to any vehicle occupant, total property damage greater than $1000, or property damage of any amount to a vehicle seized. Crash severity was assessed by police-reported vehicle damage ratings as determined by the direction of impact, type of impact, and damage location.[96] Severity ratings ranged from 0 (no damage) to 7 (severe damage). Serious or severe crashes were defined as those with a vehicle damage rating of at least 3 (i.e., crashes that resulted in more than minor dents or gouges, such as crumpling of vehicle body sheet metal and/or deformation of the structure or frame).

Maternal Injury

Maternal injury was defined as an injury to a pregnant driver due to a crash, as reported by the investigating police officer at the scene. Using a five-point scale (i.e., KABCO),[97] this outcome was classified as no injury, possible injury (i.e. no visible injury, but person complains of pain, or has been momentarily unconscious), non-disabling injury (i.e. obvious injury, such as bruises, swelling, and soreness, that is not serious enough to prevent the person from engaging in normal activities), disabling injury (i.e. obvious injury, such as massive blood loss, fractures, unconsciousness, that prevents the person from engaging in normal activities for at least one day post-collision), or fatality. Crash-related deaths included those that occurred at the time of the crash and up to one year after the crash.

Gestational age

There are two measures of gestational age in the live birth records and three measures in the fetal death records, including the self-reported date of LMP, the clinical estimate (i.e., gestational age estimated from ultrasound or other techniques), and the physician's estimate (i.e., gestational age estimated from pregnancy history, early ultrasound, or examination of the stillborn infant). The latter is only included in fetal death records. For this study, we estimated gestational age using the same method that is used by the National Center for Health Statistics for estimating gestational age in U.S. vital statistics.[98,99] This methodology relies primarily on LMP-based estimates with replacement of unreasonable values (i.e., estimates that are implausible when considering birth weight) or missing values by clinical or physician's estimates. Detailed information about the estimation of gestational age is described on page 38.

Fetal outcomes

Preterm birth was defined as a live birth that occurred between 20 and 37 weeks of gestation. Live births occurring before the 20th week of gestation (n=455) were excluded from this study. Stillbirth was defined as an intrauterine death that occurred after the 20th week of gestation. Stillbirths occurring prior to the 20th week of gestation are not reported in NC vital records.

Obstetric conditions

Obstetric complications, as recorded on the live birth and fetal death certificates, were placental abruption (i.e., separation of the placenta from the uterus during pregnancy) and premature rupture of the membranes (PROM) (i.e., spontaneous rupture of the amniochorionic membrane occurring 12 or more hours before the onset of labor).

Additional covariates

Based on a directed acyclic graph (DAG) representing our review of the literature,[3,5,100] several covariates were selected for examination (Table A.1). Covariates obtained from the live birth and fetal death certificates consisted of gestational age, maternal age, maternal race, Hispanic ethnicity, maternal education, marital status, prenatal tobacco use, prenatal alcohol use, prenatal care initiation, and parity (defined as the total number of live births including the index birth). Maternal race and Hispanic ethnicity were combined into one measure with four categories, including non-Hispanic (NH) white, NH black, other NH race (i.e., American Indian, Asian, Pacific Islander), and Hispanic. Variable specifications for vital records data are provided in Table 3.3.

The potential risk factors obtained from the motor vehicle crash reports consisted of crash-specific driver characteristics (i.e., suspected alcohol use at the time of the crash, seat belt use), vehicle characteristics (i.e., airbag deployment, estimated vehicle speed at impact, vehicle damage severity, vehicle type, number of occupants), and environmental characteristics (i.e., ambient light, crash locality, road surface, and weather condition). Variable specifications for crash records data are provided in Table 3.4.

Table 3.3. Variable specifications for vital records data

Variable	Type	Description
Exposures and/or covariates		
Maternal age[a]	Categorical	1=16-17 years, 2=18-24 years, 3=25-34 years, 4=35+ years
Gestational age (SA 1)	Continuous	Pregnancy weeks
Gestational age (SA 2, at time of crash)[b]	Categorical	1=20-27 weeks, 2=28-32 weeks, 3=33-36 weeks, 4=37+ weeks
Gestational age (SA 3)	Continuous	Pregnancy days
Gestational age (SA 3)	Ordinal	1=20-27 weeks, 2=28-32 weeks, 3=33-36 weeks, 4=37+ weeks
Maternal race & Hispanic ethnicity	Categorical	0=Non-Hispanic white, 1=Non-Hispanic black, 2=Hispanic, 3=Non-Hispanic other
Maternal education	Categorical	1=Less than high school, 2=High school graduate, 3=Some college, 4=College graduate
Marital status	Binary	0=Married, 1=Unmarried
Prenatal tobacco use	Binary	0=No prenatal tobacco use, 1=Prenatal tobacco use
Prenatal alcohol use	Binary	0=No prenatal alcohol use, 1=Prenatal alcohol use
Prenatal care initiation (SA 1&2)	Binary	0=Care initiated before the 20th week, 1=Care not initiated before the 20th week
Prenatal care initiation (SA 3)	Ordinal	0=No prenatal care, 1=Care initiated in the 1st trimester, 2=Care initiated in the 2nd trimester, 3=Care initiated in the 3rd trimester
Parity	Categorical	0=No prior live births, 1=One prior live birth, 2=Two or more prior live births
Outcomes		
Preterm birth (SA 3)	Binary	0=No preterm birth, 1=Preterm birth
Stillbirth (SA 3)	Binary	0=No stillbirth, 1= Stillbirth
Placental abruption (SA 3)	Binary	0=No placental abruption, 1=Placental abruption
PROM (SA 3)	Binary	0=No PROM, 1= PROM

Abbreviations: SA, specific aim; PROM, premature rupture of the membranes
[a]As an adjustment variable (SA 2 & 3), maternal age was coded as a quadratic spline with knots at 18, 24, 35
[b]As an adjustment variable (SA 2), gestational age was coded as a quadratic spline with knots at 35, 40

Table 3.4. Variable specifications for crash records data

Variable	Type	Description
Exposures and/or covariates		
Motor vehicle crash (SA 3)	Categorical	0=No crash, 1=One crash, 2=Two or more crashes
Alcohol use (at the time of crash)	Binary	0=No alcohol use, 1=Alcohol use
Seat belt use	Binary	0=Belt use, 1=No belt use
Airbag deployment status	Categorical	0=No airbag present, 1=Airbag present, not deployed, 2=Airbag present, deployed
Vehicle speed at impact[a]	Categorical	1=Less than 25mph, 2=25-45mph, 3=45+ mph
Vehicle damage severity[b]	Binary	0=Not severe (rating 0-2), 1=Severe (rating 3-7)
Vehicle type	Binary	0=Other non-passenger car, 1=Passenger car
Number of occupants	Categorical	1=Driver only, 2=Two occupants, 3=Three or more occupants
Ambient light	Binary	0=Daylight, 1=Darkness
Crash locality	Categorical	0=Mixed (30-70% developed), 1=Rural (<30% developed), 2=Urban (>70% developed)
Road surface condition	Categorical	0=Dry, 1=Wet, 2=Snow or ice, 3=Other (sand, gravel, oil)
Weather condition	Categorical	0=Clear, 1=Cloudy, 2=Rainy or snowy, 3=Other (fog, smoke, wind)
Outcomes		
Severe crash (SA 1)	Binary	0=No severe crash after the 20th week, 1=At least one severe crash after the 20th week
Non-severe crash (SA 1)	Binary	0=No non-severe crash after the 20th week, 1=At least one non-severe crash after the 20th week
Injury (SA 2)	Binary	0=No injury, 1=Any injury

Abbreviations: SA, specific aim; mph, miles per hour

[a]As an adjustment variable (SA 2), speed was coded as a quadratic spline with knots at 25, 45, 65

[b]As an adjustment variable (SA 2), vehicle damage severity was coded as a quadratic spline with knots at 2, 4, 6

Statistical analysis for specific aims

Specific Aim 1

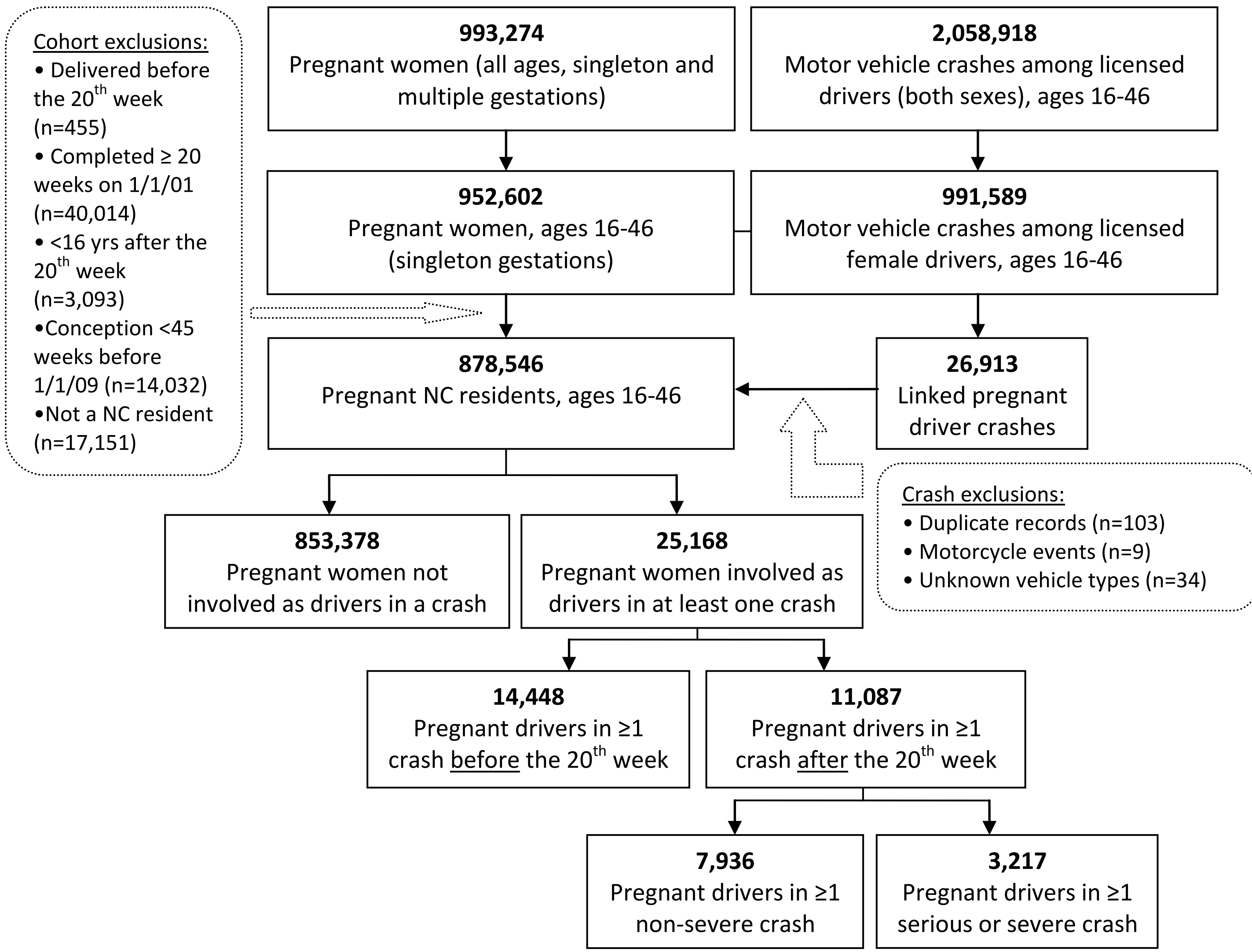
Study population

The study population was comprised of 878,546 pregnant NC residents, aged 16-46 years, who reached the 20th week of pregnancy and completed their pregnancy between January 1, 2001 and December 31, 2008 (Figure 3.2). They were identified from live birth and fetal death records that were obtained from the NCSCHS (n=993,274). These records excluded live births resulting in special registration (i.e., adoption, witness protection) and fetal deaths from induced abortions (<1% of all records) and those occurring before 20 weeks. We removed women aged less than 16 years at the time of delivery (n=7,075) because driver crashes in this pre-licensure age group are rare. In addition, we excluded women older than 46 years at delivery (n=237) and those with multiple gestation pregnancies (n=33,360) since advanced maternal age and multifetal gestation status are associated with a greater risk of adverse pregnancy outcomes.

We also excluded records if there were missing data for one or more of the following: gestational age at delivery (n=481), plurality (n=91), or mother's age (n=73). There were 73,453 women who did not meet the cohort definition, including those who delivered before completing the 20th week of pregnancy (n=455), completed 20 or more weeks of pregnancy on January 1, 2001 (n=40,014), were less than 16 years old at the 20th week of pregnancy (n=3,093), became pregnant less than 45 weeks before January 1, 2009 (n=14,032), and/or were not residents of North Carolina (n=17,151). The characteristics of the study population are presented in Table 4.1.

Following the record linkage (refer to pages 32-38), we identified 25,168 pregnant women in our study population who were drivers in one or more crashes during pregnancy; 14,448 (57%) were in at least one crash before the 20th week of pregnancy and 11,087 (44%) were in at least one crash after the 20th week (Figure 3.2). Our population at risk of a crash only included women who completed the 20th week of pregnancy because vital records lack information on early fetal losses and terminations making it impossible to obtain an accurate denominator of the number of pregnancies before 20 weeks. Therefore, only women in crashes after the 20th week were counted as having been in a crash. Of the 11,087 pregnant drivers who were in at least one crash after the 20th week, 7,936 were in at least one non-severe crash and 3,217 were in at least one serious or severe crash.

Figure 3.2. Flow chart to estimate the number of pregnant drivers who were in severe or non-severe motor vehicle crashes after the 20th week of pregnancy in North Carolina, 2001-2008



Statistical analysis

We used linear risk regression (i.e., generalized linear model with an identity link and binomial distribution) to estimate the risk of being a pregnant driver in a motor vehicle crash after the 20th week of pregnancy and to estimate risk differences for selected crash determinants (Table 3.5). DAGitty software (v1.1)[101] was used to identify the adjustment sets of covariates for the associations between maternal characteristics and the risk of being a pregnant driver in a crash (Table A.2). The DAG provided different adjustment sets for each of these associations. In addition, more than one minimally sufficient set was identified for estimating crash risks by prenatal tobacco use, alcohol use, and parity. We selected the adjustment set that allowed the model to meet the convergence criteria.

For estimating the non-severe crash risks by prenatal care, we removed maternal race and Hispanic ethnicity from the adjustment set in order to meet the convergence criteria. We assumed that the removal of this variable had no effect on our estimates since further examination of risk estimates from other crash risk models showed no noticeable differences with or without adjustment for maternal race and Hispanic ethnicity. In this analysis, all exposure and adjustment variables were modeled as categorical variables (Table 3.3).

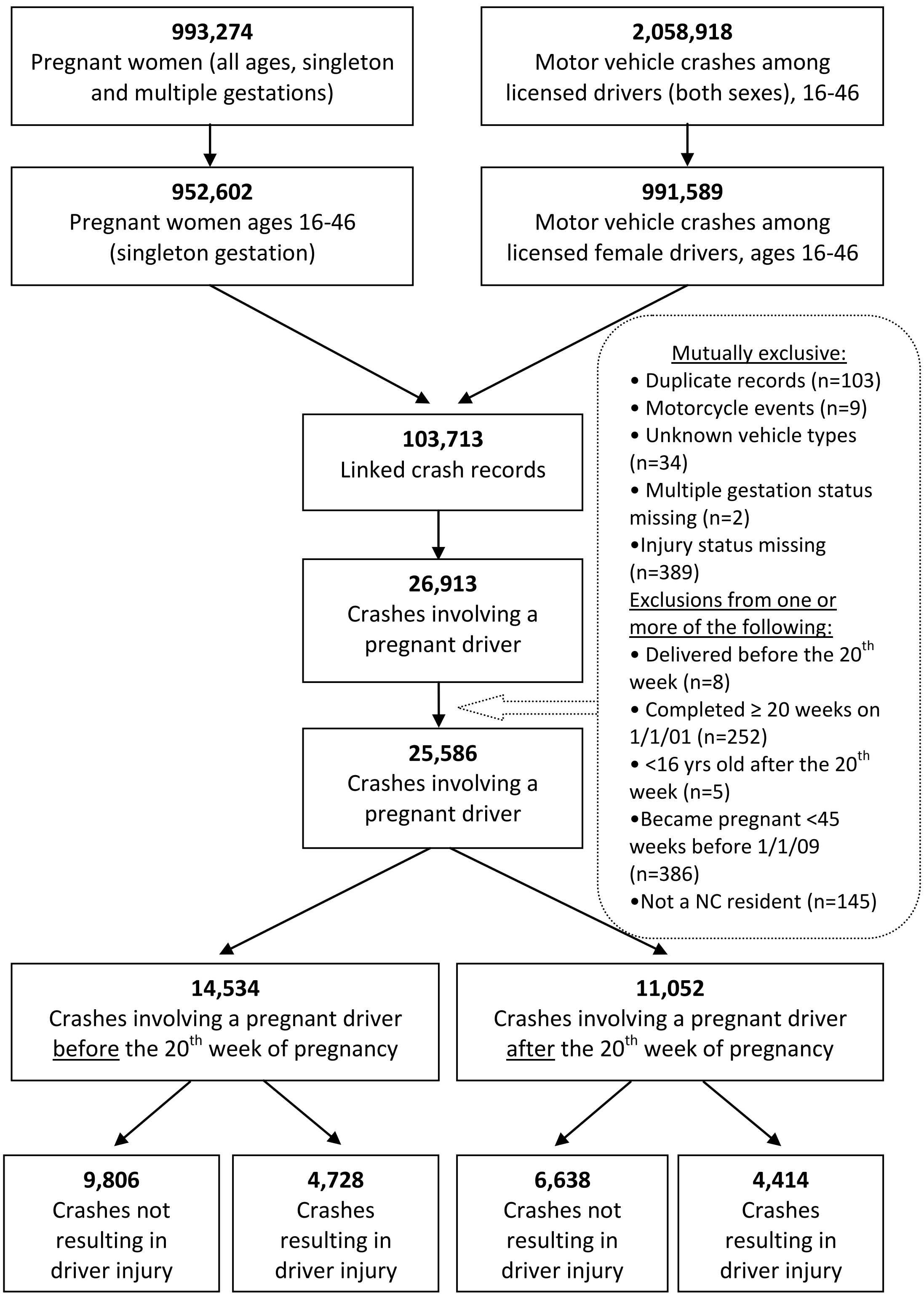
Specific Aim 2

Study population

The study population was comprised of 11,052 pregnant NC drivers, aged 16-46 years, who were in crashes and completed their pregnancy after the 20th week of pregnancy between January 1, 2001 and December 31, 2008 (Figure 3.3). They were identified from live birth and fetal death records from the NCSCHS (n=993,274). We removed records for pregnant women aged less than 16 years at delivery (n=7,075) because driver crashes in this pre-licensure age group are rare. We also excluded women older than 46 years at delivery (n=237) and those with multiple gestation pregnancies (n=33,360) in anticipation of further analyses to examine pregnancy outcomes following crashes. In general, older maternal age and multifetal gestations are associated with a higher risk of adverse pregnancy outcomes.

Following the record linkage (refer to pages 32-38), there were 26,913 crashes identified as having involved a pregnant driver. We excluded 103 duplicate records (i.e., 56 duplicate crash records, 39 duplicate vital records, and 8 vital records that linked to both vehicles in a two-car crash). We also excluded 34 records with unknown vehicle types, 9 records in which the pregnant driver was riding a motorcycle since these vehicles and their safety devices differ from passenger cars and trucks, and records missing data for injury status (n=389) or multiple gestation status (n=2). From these, there were 790 pregnant drivers in crashes who did not meet the cohort definition, including those who delivered before completing the 20th week of pregnancy (n=8), completed 20 or more weeks of pregnancy on January 1, 2001 (n=252), were less than 16 years old at the 20th week of pregnancy (n=5), became pregnant less than 45 weeks before January 1, 2009 (n=386), and/or were not residents of North Carolina (n=145). The final cohort included 25,586 pregnant drivers in crashes; 14,534 (57%) were in crashes in the first 20 weeks of pregnancy and 11,052 (43%) were in crashes after the 20^{th} week. Although crashes occurred at any time during pregnancy, it was impossible to obtain an accurate denominator of pregnant drivers in crashes before 20 weeks due to the lack of information for early fetal losses and terminations in vital records. Therefore, only drivers in crashes after the 20^{th} week were examined. The characteristics of the study population are presented in Table 5.1.

Figure 3.3. Flow chart to estimate the number of pregnant drivers who were injured in motor vehicle crashes after the 20th week of pregnancy in North Carolina, 2001-2008



Statistical analysis

We used linear risk regression (i.e., generalized linear model with an identity link and binomial distribution) to model the risk of injury and to estimate risk differences and the number needed to treat (NNT) for selected injury risk factors (Table 3.5).[102] NNTs were calculated by dividing 1 over the risk difference estimates and can be interpreted as, on average, the number of people who need to be treated (or "exposed" to a particular risk factor) to increase or decrease the number of injured drivers by one. We considered generalized estimating equations (GEEs) to account for correlated observations among pregnant drivers in multiple crashes in the same pregnancy (Table B.1). We were unable to reliably identify drivers who were in multiple crashes across different pregnancies.

DAGitty software (v1.1)[101] was used to identify the appropriate adjustment sets of covariates for the associations between maternal and crash characteristics and the risk of injury (Table A.3). The DAG provided different adjustment sets for each of these associations. For selected risk factors (i.e., race and Hispanic ethnicity, suspected alcohol use, belt use, vehicle speed, vehicle type, number of occupants, ambient light, crash locality, road surface, and weather condition), the DAG analysis identified more than one minimally sufficient set. We conducted a sensitivity analysis to examine the effect of these adjustment sets on the estimated risk differences. All of the exposure variables were modeled as categorical variables; gestational age at the time of the crash, vehicle damage severity, and vehicle speed (as adjustment variables) were modeled as quadratic splines with knots at each categorical cutpoint (Table 3.4).

Specific Aim 3

Study population

The study population was comprised of 878,546 pregnant NC residents, aged 16-46 years, who reached the 20th week of pregnancy and delivered a live or stillborn singleton infant between January 1, 2001 and December 31, 2008. These women completed a total of 115,797,259 pregnancy days following the 20th week of pregnancy. They were identified from live birth and fetal death records that were obtained from the NCSCHS (n=993,274). The same criteria used to define the cohort in the analysis for Specific Aim 1 were applied to this study population (refer to page 44). The characteristics of the study population are presented in Table 6.1.

Statistical analysis

We used Poisson regression to estimate rate ratios for the associations between motor vehicle crashes and preterm birth, stillbirth, placental abruption, and PROM (Table 3.5). Person-time at risk was defined as pregnancy days completed after the 20th week of pregnancy. Incidence rates were defined as the number of events (i.e., preterm birth, stillbirth, placental abruption, or PROM) divided by the total number of pregnancy days completed after the 20th week, within each crash exposure category. For the estimation of preterm birth rates, only live births (numerator) and pregnancy days (denominator) that occurred between 20 and 37 weeks were counted. For all other pregnancy outcomes, the estimated rates included all events and days that occurred between the 20th week and the completion of the pregnancy.

For this analysis, the number of crashes during pregnancy was modeled as a time-dependent exposure, thus an individual woman could contribute time to more than one crash exposure category if she was a driver involved in more than one crash during the same pregnancy. For example, if a woman was a driver involved in one crash on day 200 of her pregnancy, then her exposure status from days 140 to 199 was classified as "no crash" and her exposure status from days 200 to delivery was classified as "first crash". In addition, if a pregnant woman was involved in any crashes before the 20th week of pregnancy, then her exposure status at the start of the risk period was classified according to the total number of prior crashes. For example, if a pregnant woman was a driver involved in two crashes before the 20th week of pregnancy, then her exposure status from days 140 to delivery was classified as "second or subsequent crashes".

We used DAGitty software (v1.0)[101] to identify the appropriate adjustment sets of covariates for the association between crashes and adverse pregnancy outcomes (Table A.4). The DAG provided different adjustment sets for each exposure-outcome association and there were two or more minimally sufficient sets that were identified for estimating the rates of placental abruption and PROM by crash involvement. We conducted a sensitivity analysis to examine the effect of these different adjustment sets on the estimated rate ratios for placental abruption and PROM. Gestational age and trimester of prenatal care initiation were modeled as time-varying covariates. Maternal age was modeled as a quadratic spline with knots at each categorical cutpoint; gestational age was modeled as an ordinal variable (Table 3.3). We conducted additional analyses to examine whether modeling gestational age as a continuous variable (vs. a categorical variable) had an effect on the rate ratio estimates. We found that the estimates from the analyses with gestational age modeled as a continuous variable were not noticeably different from the estimates with gestational age modeled as a categorical variable.

We also conducted additional analyses to assess the specification of the model (Table C.1). We used log-binomial regression (i.e., generalized linear model with a log link and binomial distribution) to examine the association between pregnant driver crashes before the start of the risk period (i.e., 0, 1, 2 or more crashes) and the risk of preterm birth, stillbirth, placental abruption, and PROM. For this analysis, we assessed four risk periods and each started at a different week of pregnancy (i.e., 20, 24, 28, and 32 weeks).

Table 3.5. Statistical analysis plan, by specific aim, to examine motor vehicle crashes and adverse maternal and fetal outcomes among pregnant drivers in North Carolina, 2001-2008.

Research Question	Study Population/Risk Period	Exposure (s)	Outcome (s)	Measure	Analysis
Specific Aim 1: *Estimate the risk and describe the risk factors for being a pregnant driver in a motor vehicle crash after the 20th week of pregnancy in NC between 2001 and 2008.*					
What is the risk (and what are the risk factors) of being a pregnant driver in a crash after the 20th week of pregnancy among pregnant women in North Carolina between 2001 and 2008?	**Study Population:** Pregnant NC residents, aged 16-46 years, who reached the 20th week of pregnancy and completed their pregnancy between January 1, 2001 and December 31, 2008. (n=878,546) **Risk Period:** The risk period starts after the 20th week and ends at the completion of the pregnancy.	1. Maternal age 2. Gestational age 3. Race & ethnicity 4. Education 5. Marital status 6. Prenatal tobacco use 7. Prenatal alcohol use 8. Parity	1. Motor vehicle crash	Risk	Linear risk regression (identity link, binomial distribution)
Specific Aim 2: *Estimate the risk and describe the risk factors for sustaining crash-related maternal injuries among pregnant NC drivers who were in crashes after the 20th week of pregnancy between 2001 and 2008.*					
What is the risk (and what are the risk factors) of maternal injury among pregnant drivers who were in crashes after the 20th week of pregnancy?	**Study Population:** Pregnant NC drivers, aged 16-46 years, who were in a crash after the 20th week of pregnancy and completed their pregnancy between January 1, 2001 and December 31, 2008. (n=11,052) **Risk Period:** The risk period starts and ends at the time of the crash.	1. Maternal age 2. Gestational age 3. Race & ethnicity 4. Alcohol use (at crash) 5. Belt use 6. Airbag status 7. Vehicle speed 8. Vehicle damage 9. Vehicle type 10. Number of occupants 11. Ambient light 12. Crash locality 13. Road surface	1. Crash-related maternal injury	Risk	Linear risk regression (identity link, binomial distribution)

		14. Weather condition			
Specific Aim 3: *Examine the association between motor vehicle crashes involving a pregnant NC driver and the rate of preterm birth, stillbirth, placental abruption, and premature rupture of the membranes.*					
Is there an association between motor vehicle crashes and an elevated rate of preterm birth, stillbirth, placental abruption, or PROM?	**Study Population:** Pregnant NC residents, aged 16-46 years, who reached the 20^{th} week of pregnancy and completed their pregnancy between January 1, 2001 and December 31, 2008. (n=878,546) **Risk Period:** The risk period starts after the 20^{th} week and ends at the 37^{th} week (for preterm birth) or at the completion of the pregnancy (for stillbirth, placental abruption, and PROM).	1. Motor vehicle crash (time-dependent)	1. Preterm birth 2. Stillbirth 3. Placental abruption 4. PROM	Rate	Poisson regression (log link, Poisson distribution)

Abbreviations: PROM, premature rupture of the membranes

IV. RESULTS: THE RISK OF BEING A PREGNANT DRIVER IN A MOTOR VEHICLE CRASH IN NORTH CAROLINA, 2001-2008

Introduction

In the United States, motor vehicle crashes are the leading non-obstetric cause of maternal death during pregnancy. A pregnant occupant crash rate of 13 per 1,000 person-years was estimated from a probability sample of pregnant occupant crashes in the U.S., while a rate of 26 per 1,000 person-years was estimated for non-pregnant women during the same period.[1] However, the pregnant occupant crash rate is likely an underestimate due to difficulties in capturing cases. Statewide crash surveillance is lacking and administrative databases are limited, as crash records lack information on pregnancy status and vital records lack data on crash history.

A few studies have addressed these limitations by using linked data sources (i.e., police crash reports and vital records) to estimate state-level pregnancy crash risks.[3,4,7] These risks (ranging from 1.0% to 2.8%) are better estimates of crashes during pregnancy, but the denominators do not account for variable time spent driving a motor vehicle during pregnancy. A recent study suggested that these estimates may be on the "lower end of the risk spectrum" since they are from states with lower severe crash risks and older maternal ages at birth (i.e., Washington, Pennsylvania) or younger maternal ages (i.e., Utah), compared to other states, such as North Carolina (NC) that have higher crash risks among reproductive-aged women.[7]

In the general population, there are several known factors that influence crash exposure and involvement, including young age,[100] Hispanic ethnicity,[103] tobacco use,[104,105] alcohol use,[100] and driver fatigue.[100] However, little is known about the determinants of crashes among pregnant women. To increase awareness regarding the risk of crashes during pregnancy and to inform the development of effective crash prevention strategies, it is important to quantify the pregnant driver crash risk and to understand what factors contribute to this risk. Our objectives were to use linked data sources in NC to estimate the risk and examine risk factors for being a pregnant driver in a crash.

Methods

Study population

We examined a cohort of 878,546 pregnant NC residents, aged 16-46 years, who reached the 20th week of pregnancy and delivered a live or stillborn singleton infant in NC between January 1, 2001 and December 31, 2008. These women were identified from live birth and fetal death records from the NC State Center for Health Statistics (n=993,274). We removed records for pregnant women aged less than 16 years at the time of delivery (n=7,075) because driver crashes in this age group are uncommon. We also excluded women older than 46 years at delivery (n=237) and those with multiple gestation deliveries (n=33,360) in anticipation of further analyses to examine pregnancy outcomes following crashes since advanced maternal age and multifetal gestation are associated with a greater risk of adverse pregnancy outcomes. Additional records were excluded if there were missing data for mother's age (n=73), multiple gestation status (n=91) and/or gestational age (n=481). There were 73,453 women who did not meet the cohort definition.

Probabilistic record linkage

To identify women who were pregnant drivers in crashes in NC, individual vital records were probabilistically linked to state crash records using mother's name, date of birth, race, and residential county. We compared the date of the last menstrual period (LMP) to the crash date to ensure that the crash occurred during pregnancy. Using the same method that is commonly used for estimating gestational age in U.S. vital statistics,[98,99] we replaced LMP-based estimates with the clinical estimate if the LMP date was missing or provided an implausible gestational age (i.e., based on comparing weeks of gestation with birth weight, n=51,593). If the LMP date and clinical estimate were both missing (n=531), the physician's estimate (i.e., estimated from pregnancy history, early ultrasound, or examination of the stillborn infant), if known, was used for fetal deaths. If all values were missing (n=481), then crash involvement could not be determined. This linkage was performed using LinkSolv generalized linkage software (Strategic Matching Inc., Morrisonville, NY, 2009).

There were 26,913 motor vehicle crashes identified as having involved a pregnant driver. We excluded 103 duplicate records, records with unknown vehicle types (n=34) and those in which the driver was riding a motorcycle (n=9) since these vehicles and their safety devices differ from passenger cars and trucks. After defining the cohort, we identified a total of 25,168 pregnant women who were drivers involved in one or more crashes; 14,448

(57%) were in at least one crash before the 20th week of pregnancy and 11,087 (44%) were in at least one crash after the 20th week. Since it was impossible to obtain an accurate denominator of the number of pregnancies before 20 weeks due to the lack of information for early fetal losses and terminations in vital records, our population at risk of a crash only included women who completed the 20th week of pregnancy. Therefore, only women in crashes after the 20th week were counted as having been in a crash (n=11,087).

Measures

Motor vehicle crashes and crash severity

A police-reported crash on a public roadway involved a NC licensed pregnant driver of a motor vehicle or passenger truck beyond the 20th week of pregnancy. Crash reports are completed by police if the crash resulted in a fatality or non-fatal personal injury to any vehicle occupant, total property damage greater than $1000, or property damage of any amount to a vehicle seized. Only crashes involving a NC licensed driver were included because identifiers from the driver license records were needed for the linkage. Identifying information for passengers was not available from the crash reports.

Crash severity was assessed by police-reported vehicle damage ratings as determined by the direction of impact, type of impact, and damage location.[96] Severity ratings ranged from 0 (no damage) to 7 (severe damage). For this study, serious or severe crashes were defined as those with a vehicle damage rating of at least 3 (i.e., crashes that resulted in more than minor dents or gouges, such as crumpling of sheet metal and/or deformation of the structure or frame).

Determinants of crashes

Based on a directed acyclic graph (DAG) representing a review of the literature,[3,5,100] several risk factors for crashes were selected for examination (Table A.1). Potential crash determinants included gestational age, maternal age, race, Hispanic ethnicity, education, marital status, prenatal tobacco and alcohol use, prenatal care before the 20th week, and parity (i.e., the total number of live births including the index birth). We combined maternal race and Hispanic ethnicity into one measure with four categories, including non-Hispanic (NH) white, NH black, other NH race (i.e., American Indian, Asian, Pacific Islander), and Hispanic.

Statistical analysis

We used binomial regression to model the risk of being a pregnant driver in a motor vehicle crash after the 20th week of pregnancy and to estimate risk differences for selected crash determinants. These absolute measures of risk were estimated instead of relative measures of risk to better convey the public health implications of our findings.[106,107] DAGitty software (v1.1)[101] identified the adjustment sets of covariates for the associations between maternal characteristics and the risk of being a pregnant driver in a crash (Table A.2). The DAG provided different adjustment sets for each of these associations. In addition, more than one minimally sufficient set was identified for estimating crash risks by prenatal tobacco use, alcohol use, and parity. We selected the adjustment set that allowed the model to meet the convergence criteria.

For estimating the non-severe crash risk by prenatal care, we removed maternal race and Hispanic ethnicity from the adjustment set in order to meet the convergence criteria. We assumed that the removal of this variable had no effect on our estimate since further examination of risk estimates from other crash risk models showed no noticeable differences with or without adjustment for maternal race and Hispanic ethnicity. This study was approved by the Institutional Review Board of the University of North Carolina at Chapel Hill.

Results

Study population

A total of 878,546 pregnant women were included in the cohort in 2001-2008. High proportions of these women were 25-34 years, non-Hispanic white, educated at least through high school, married, did not use any tobacco or alcohol during pregnancy, began prenatal care before the 20th week of pregnancy, and had no prior live births (Table 4.1). The mean number of weeks of pregnancy completed by women in this cohort was 38.7 weeks (standard deviation=2.7); the median was 39.0 weeks.

There were 11,087 pregnant women (12.6 per 1,000 pregnant women) who were drivers in at least one crash after the 20th week of pregnancy; 3,217 women were in at least one serious or severe crash (3.7 per 1,000 pregnant women) (Table 4.1) and 7,936 were in at least one non-severe crash (9.0 per 1,000 pregnant women) (Table 4.2). The majority (98%) of pregnant drivers in a crash were involved in only one crash (n=10,931); 153 were involved in two, and 3 in three crashes.

Crash determinants

Pregnant women aged 18-24 years (vs. 25-34 years), NH black (vs. NH white), with high school diplomas only or some college (vs. college graduates), unmarried, who used tobacco, or delivered two or more prior live births (vs. no prior live births) were at higher risk of being a driver in a serious or severe crash (Table 4.1). The severe crash risk estimate was also elevated for women who delayed prenatal care initiation. Pregnant women who were 16-17 years or 35 years or older (vs. 25-34 years), Hispanic (vs. NH white), or prenatal alcohol users were at lower risk of being a driver in a serious or severe crash. Determinants for non-severe crashes were similar (Table 4.2). However, pregnant women who completed less than high school (vs. college graduates) or delayed prenatal care initiation had a lower risk of being a driver in a non-severe crash.

Driver crash risks based on two-week intervals (i.e., estimated as the number of pregnant drivers in crashes during each two-week period divided by the total number of women who were pregnant at the beginning of each two-week period) remained relatively constant at 1.5 per 1,000 pregnant women (standard error, SE, 0.04) from 20-31 weeks of pregnancy (Figure 4.1). The driver crash risk declined after 31 weeks with the lowest risk (0.04 per 1,000 pregnant women, SE=0.02) estimated between 40 and 42 weeks.

Discussion

Previous state-level linkage studies have estimated pregnancy crash risks that ranged from 1.0% among pregnant front seat occupants (i.e., drivers and passengers) in Washington State[4] to 2.8% among pregnant drivers in Utah.[3] A recent study in

Pennsylvania[7] reported a crash risk of 1.1% among pregnant drivers. However, these studies counted crashes that occurred at any detectable time during pregnancy, despite the undercount of pregnancies at risk early in pregnancy, owing to the high frequency of fetal loss during that period and the lack of vital records reporting early losses and terminations. If we had calculated our driver crash risk using the same method as these other states (i.e., by counting all crashes that occurred during pregnancy), then NC would have appeared to have the highest reported pregnant driver crash risk (25,168/878,546=2.9%). This result confirms the prediction by Weiss et al.[7] that a state, such as NC, with a higher birth rate among younger mothers and a higher severe crash risk among young women of reproductive age, should have a higher crash risk among pregnant women.

We identified maternal characteristics that may increase a pregnant woman's risk of being in a crash, including young age (i.e., 18-24 years), black race, less education, unmarried status, tobacco use, and two or more prior births. Previous research found a higher proportion of women who crashed during pregnancy to be younger,[3,5] non-white,[5] less educated,[5] unmarried,[5] tobacco users,[3,5] and have fewer previous births[3] than pregnant women who were not in crashes. Young drivers, in general, have an increased crash risk because of their inexperience and greater involvement in risky behaviors (i.e., speeding, substance use).[100,108] The higher crash risk among black women may be due to social and behavioral factors that we were unable to measure (e.g., driving patterns, car ownership). Although the association between marital status and crash risk is not well studied, previous research found married adults to be healthier and less likely to engage in risky behaviors.[109] Tobacco users may have a higher crash risk because of holding or lighting a cigarette while driving or greater involvement in other risky behaviors.[104,105] In general populations, fatigue is a known crash determinant[100] and may explain the increased crash risk for multiparous women since parity can affect sleep.[110]

We also found that pregnant women were at lower risk of being drivers in crashes during later weeks of pregnancy. This may be attributed to a lower frequency of driving during that time. Hispanic women were also at lower risk of being drivers in crashes. We expected higher crash risks for these women since Hispanics, in general, have an increased involvement in crashes.[103] Although pregnant women who did not graduate from high school or delayed prenatal care initiation were at higher risk of being in a severe crash, they were at lower risk of being in a non-severe crash. Based on previous research, we expected driver crash risks to be consistently higher among pregnant women with less education and those who delayed prenatal care.[5] Overall, explanations for many of these associations are unclear from the literature.

Strengths and limitations

This study is subject to several limitations. We were unable to quantify the amount of time or miles women spent driving a motor vehicle during pregnancy and cannot confine the denominator of our estimates to person-time spent driving. We instead estimated the number of women at risk of being a driver in a crash among all pregnant women who completed the 20th week of pregnancy, regardless of how much they drove. Therefore, our reported estimates may be biased if they are associated with driving time.

We were unable to observe pregnancies that ended before the 20th week, women who moved out of NC during pregnancy, out-of-state crashes that involved pregnant NC drivers, and pregnant driver crashes that did not link to vital records. Although most pregnant women are involved in crashes in the U.S. as drivers (70%),[1] like most prior studies, we could not identify women in our study population who were passengers in crashes due to the lack of identifying information in the crash reports. Therefore, our findings can only be generalized to being a pregnant driver in a crash.

There is the potential for misclassification of measures from the vital records. Gestational age was used to determine whether a crash occurred during pregnancy, but these estimates are unreliable in vital records data, especially those based on LMP.[98,111-113] To address this limitation, we estimated gestational age using the same method that is used by the National Center for Health Statistics,[98,99] by creating a composite measure that did not rely solely on the date of LMP, but also used clinical or physician's estimates when LMP estimates were unreasonable or missing. Previous studies have assessed the validity and reliability of several measures from the NC birth records by comparing them to other data sources.[114,115] They measured high agreement for maternal demographics and prenatal care and moderate or poor agreement for behavioral risk factors (e.g., prenatal tobacco and alcohol use).[114,115] These limitations should be considered when interpreting the results.

This study has several strengths, including the large size and diversity of the cohort enumerated over an eight-year study period and the use of record linkage methodology to ascertain crashes during pregnancy that are not otherwise documented.

As one of only four states that have used linked records to quantify the risk of being a pregnant driver in a crash, NC appears to have the highest risk. This risk is especially elevated among pregnant women who are 18-24 years, non-Hispanic black, less than college educated, or unmarried. Health care providers should use this information to educate their patients about the risk of being a driver in a crash during pregnancy, particularly in the second trimester when they are at highest risk. Additionally, women can be encouraged to decrease their crash risk by modifying their driving use and driving behaviors. More research is needed to better quantify the frequency and patterns of driving during pregnancy, particularly among those at highest risk of being in a crash.

Tables

Table 4.1. Maternal characteristics for being a driver in a serious or severe motor vehicle crash after the 20th week of pregnancy in North Carolina (N=878,546), 2001-2008.

	Pregnant women		At least One Serious or Severe[a] Motor Vehicle Crash Involving a Pregnant Driver After the 20th Week of Pregnancy			
	N	%	N	Crash risk[b]	Risk Difference	95% CI
Overall	878,546		3,217	3.7		
Maternal age, years[c]						
16-17	26,062	3	69	2.6	-0.3	-0.9, 0.3
18-24	309,734	35	1,394	4.5	0.8	0.5, 1.1
25-34	436,285	50	1,440	3.3	0	Reference
35+	106,465	12	314	2.9	-0.3	-0.7, 0.0
Missing	0	0	0			
Race & Hispanic ethnicity[d]						
Non-Hispanic white	502,886	57	1,836	3.7	0	Reference
Non-Hispanic black	202,425	23	976	4.8	1.2	0.8, 1.5
Hispanic	135,023	15	273	2.0	-1.6	-1.9, -1.3
Non-Hispanic other	37,248	4	131	3.5	-0.1	-0.8, 0.5
Missing	964	<1	1			
Maternal education						
Less than high school	195,783	22	579	3.0	-0.03	-0.4, 0.3
High school graduate	257,144	29	1,145	4.5	1.5	1.1, 1.8
Some college	194,282	22	804	4.1	1.1	0.8, 1.5
College graduate	229,462	26	686	3.0	0	Reference
Missing	1,875	<1	3			
Marital status						
Married	548,321	62	1,681	3.1	0	Reference
Not married	330,172	38	1,536	4.7	1.6	1.3, 1.9
Missing	53	<1	0			
Prenatal care before the 20th week[e]						
Yes	828,185	95	3,024	3.7	0	Reference
No	43,438	5	168	3.9	0.02	-0.5, 0.6
Missing	6,923	<1	25			
Prenatal tobacco use[f]						
Yes	104,705	12	476	4.5	0.8	0.3, 1.2
No	772,837	88	2,735	3.5	0	Reference
Missing	1,004	<1	6			

Prenatal alcohol use[g]						
Yes	4,210	1	12	2.9	-1.0	-2.6, 0.6
No	873,252	99	3,200	3.7	0	Reference
Missing	1,084	<1	5			
Parity[h,i]						
1	359,325	41	1,286	3.6	0	Reference
2	293,943	33	1,064	3.6	0.2	-0.1, 0.5
≥3	224,800	26	865	3.8	0.6	0.3, 1.0
Missing	478	<1	2			

Abbreviations: CI, confidence interval

[a] Crash severity defined by vehicle damage rating (serious or severe= rating range 3-7)

[b]Unadjusted crash risks defined as the number of pregnant women in crashes per 1,000 pregnant women

[c]Adjusted for maternal race & Hispanic ethnicity and education

[d]'Other' race includes American Indian, Asian, Pacific Islander

[e]Adjusted for maternal age, maternal race & Hispanic ethnicity, education

[f]Adjusted for maternal age, parity, prenatal care, prenatal alcohol use

[g]Adjusted for maternal age, parity, prenatal care, prenatal tobacco use

[h]Parity indicates the total number of live births, including the index birth

[i]Adjusted for maternal age, prenatal care, prenatal tobacco use, prenatal alcohol use

Table 4.2. Maternal characteristics for being a driver in a non-severe motor vehicle crash after the 20th week of pregnancy in North Carolina (N=878,546), 2001-2008.

	Pregnant women	At least One Non-Severe[a] Motor Vehicle Crash Involving a Pregnant Driver After the 20th Week of Pregnancy			
	N	N	Crash risk[b]	Risk Difference	95% CI
Overall	878,546	7,936	9.0		
Maternal age, years[c]					
16-17	26,062	115	4.4	-2.7	-3.5, -1.9
18-24	309,734	3,119	10.1	0.9	0.5, 1.4
25-34	436,285	3,809	8.7	0	Reference
35+	106,465	893	8.4	-0.5	-1.1, 0.1
Missing	0	0			
Race & Hispanic ethnicity[d]					
Non-Hispanic white	502,886	4,465	8.9	0	Reference
Non-Hispanic black	202,425	2,475	12.2	3.3	2.8, 3.9
Hispanic	135,023	677	5.0	-3.9	-4.3, -3.4
Non-Hispanic other	37,248	313	8.4	-0.5	-1.4, 0.5
Missing	964	6			
Maternal education					
Less than high school	195,783	1,230	6.3	-2.3	-2.8, -1.7
High school graduate	257,144	2,628	10.2	1.7	1.1, 2.2
Some college	194,282	2,108	10.9	2.3	1.7, 2.9
College graduate	229,462	1,961	8.5	0	Reference
Missing	1,875	9			
Marital status					
Married	548,321	4,504	8.2	0	Reference
Not married	330,172	3,431	10.4	2.2	1.8, 2.6
Missing	53	1			
Prenatal care before the 20th week[e]					
Yes	828,185	7,575	9.1	0	Reference
No	43,438	291	6.7	-1.8	-2.6, -1.0
Missing	6,923	70			
Prenatal tobacco use[f]					
Yes	104,705	1,009	9.6	0.5	-0.1, 1.1
No	772,837	6,919	9.0	0	Reference
Missing	1,004	8			
Prenatal alcohol use[g]					
Yes	4,210	32	7.6	-0.9	-3.6, 1.7
No	873,252	7,894	9.0	0	Reference

Missing	1,084	10			
Parity[h,i]					
1	359,325	3,229	9.0	0	Reference
2	293,943	2,702	9.2	0.2	-0.3, 0.7
≥3	224,800	2,002	8.9	0.2	-0.4, 0.7
Missing	478	3			

Abbreviations: CI, confidence interval

[a] Crash severity defined by vehicle damage rating (non-severe= rating range 0-2)

[b]Unadjusted crash risks defined as the number of pregnant women in crashes per 1,000 pregnant women

[c]Adjusted for maternal race & Hispanic ethnicity and education

[d]'Other' race includes American Indian, Asian, Pacific Islander

[e]Adjusted for maternal age, education

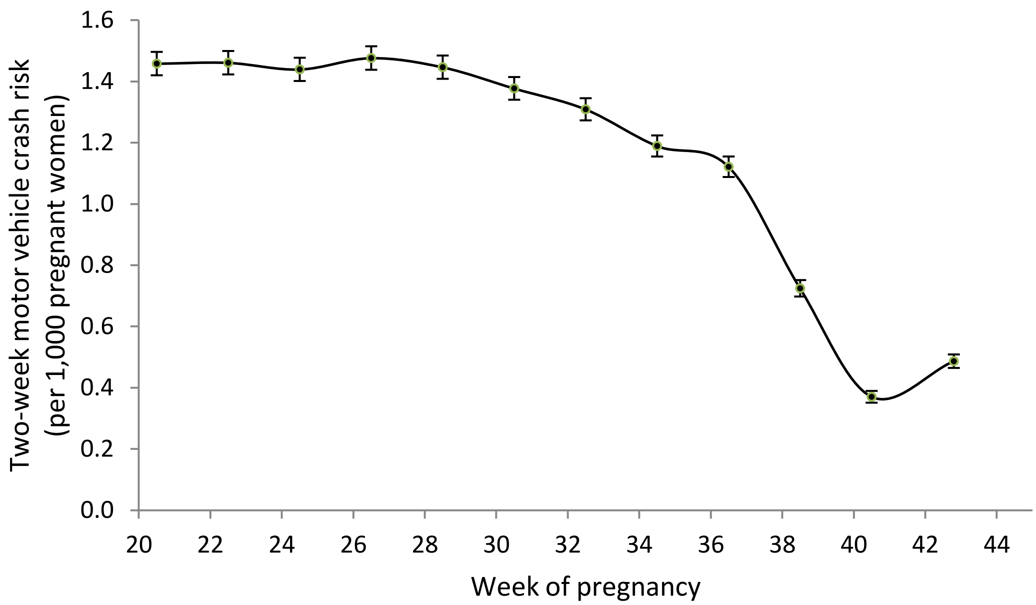
[f]Adjusted for maternal age, parity, prenatal care, prenatal alcohol use

[g]Adjusted for maternal age, parity, prenatal care, prenatal tobacco use

[h]Parity indicates the total number of live births, including the index birth

[i]Adjusted for maternal age, prenatal care, prenatal care tobacco use, prenatal alcohol use

Figure 4.1. The risk of being a driver in a motor vehicle crash after the 20th week, by week of pregnancy, among pregnant women in North Carolina (N=878,546), 2001-2008.



V. RESULTS: MOTOR VEHICLE CRASHES AND INJURIES AMONG PREGNANT DRIVERS IN NORTH CAROLINA

Introduction

Injuries from motor vehicle crashes during pregnancy are the leading cause of severe maternal morbidity and mortality in the United States. It is estimated that at least 92,500 pregnant women (2.3 per 100 live births) are injured annually in crashes across the U.S.[2] In general, crash-related maternal injuries are underreported. Injury information is often obtained from hospitalization records or is self-reported and thus only the most severe injuries are captured. However, pregnant women sustain a variety of crash-related injuries that range in severity from minor sprains to pelvic fractures, uterine and placental injury, and death.[5,20]

Ongoing crash-related maternal injury surveillance is lacking. Crash records lack information on pregnancy status, and vital records (i.e., birth certificates) lack data on injury history. Previous studies have addressed these limitations by using linked records to examine crash-related maternal injuries during pregnancy,[5,7] but only one of these studies examined both hospitalized and non-hospitalized injuries.[7] Several studies have also examined the effectiveness of vehicle safety devices, primarily seat belts[3,4,72,116] and airbags,[4] in reducing the risk of maternal injury and other adverse maternal outcomes. However, little is known about other risk factors for crash-related maternal injuries.

To better understand the risk of crash-related injuries, it is important to consider several types of factors, including demographics, vehicle characteristics, and environmental conditions. To date, these types of characteristics have not been well studied among pregnant women. Our objectives were to use a large and diverse study population from linked data sources in North Carolina (NC) to estimate the risk of injury and to examine risk factors for sustaining injuries among pregnant drivers who were in crashes.

Methods

Study population

This study included a cohort of 11,052 pregnant NC drivers, 16-46 years, who were in crashes and delivered a live or stillborn singleton infant after the 20th week of pregnancy between January 1, 2001 and December 31, 2008. They were identified from linking live birth and fetal death records for singleton infants among pregnant women aged 16-46 years (n=952,602) to state crash records for licensed female drivers in this age group (n=991,589). Records were linked by mother's first and last name, date of birth, race, and residential county and the probabilistic linkage was performed using LinkSolv generalized linkage software (Strategic Matching Inc., Morrisonville, NY, 2009). The date of the last menstrual period (LMP) was compared to the date of the crash to ensure that the crash occurred during pregnancy. If the date of LMP was missing or provided an implausible gestational age based on gestational weeks and birth weight (n=51,593), the clinical estimate was used. If both estimates were missing (n=531), the physician's estimate (i.e., estimated from pregnancy history, early ultrasound, or examination of the stillborn infant), was used only for fetal deaths. If all three values were missing (n=481), then crash involvement could not be determined and the records were excluded.

We identified 26,913 crashes that involved a pregnant driver. We excluded 103 duplicate records, 34 records with unknown vehicle types, 9 records in which the pregnant driver was riding a motorcycle since these vehicles and their safety devices differ from passenger cars and trucks, and records missing data for injury status (n=389) or multiple gestation status (n=2). From these, there were 790 pregnant drivers in crashes who did not meet the cohort definition. The final cohort included 25,586 pregnant drivers in crashes; 11,052 (43%) were in crashes after the 20th week. Since it was impossible to identify all pregnant drivers in crashes before 20 weeks due to the lack of information for early fetal losses and terminations in vital records, only drivers in crashes after the 20th week were examined.

Measures

Motor vehicle crashes

A motor vehicle crash was defined as a police-reported crash that involved a NC licensed female driver of a motor vehicle or passenger truck beyond the 20th week of pregnancy. The crash had to occur on a public roadway and result in a fatality or non-fatal personal injury to any vehicle occupant, total property damage greater than $1000, or property damage of any amount to a vehicle seized. Only crashes involving a NC licensed driver were included because identifiers from the driver license records were needed for the linkage. Crashes involving pregnant passengers were excluded since identifying information for these women was not available from the crash reports.

Maternal injury

Maternal injury was defined as a crash-related injury to a pregnant driver as reported by the investigating police officer at the scene. Using a five-point scale (i.e., KABCO),[97] this outcome was classified as no injury, possible injury (i.e. no visible injury, but person complains of pain), non-disabling injury (i.e. obvious injury that does not prevent the person from engaging in normal activities), disabling injury (i.e. obvious injury that prevents the person from engaging in normal activities for at least one day), or fatality. Deaths included those that occurred at the time of the crash and up to one year later.

Determinants of crash-related maternal injuries

Based on a directed acyclic graph (DAG) representing a review of the literature,[3,5,100] several risk factors for crash-related maternal injuries were selected for examination (Table A.1). The potential risk factors consisted of driver demographics (i.e., age, race and Hispanic ethnicity), crash-specific driver characteristics (i.e., gestational age at the time of the crash, suspected alcohol use, seat belt use), vehicle and crash characteristics (i.e., airbag deployment, estimated vehicle speed at impact, crash severity, vehicle type, number of occupants), and environmental characteristics (i.e., ambient light, crash locality, road surface, and weather condition).

We combined race and Hispanic ethnicity into one measure with four categories, including non-Hispanic (NH) white, NH black, other NH race (i.e., American Indian, Asian, Pacific Islander), and Hispanic. Crash severity was assessed by police-reported vehicle damage ratings (ranging from 0-7 for none to severe damage) as determined by the direction of impact, type of impact, and damage location.[96] We defined serious or severe crashes as those with a vehicle damage rating of at least 3 (i.e., crashes with more than minor dents or gouges, such as crumpling of sheet metal and/or deformation of the frame). Additional covariates in the DAG included maternal education, marital status, prenatal tobacco use, prenatal alcohol use, prenatal care before the 20th week of pregnancy, and parity (i.e., total number of live births including the index birth). We obtained data for the maternal characteristics from vital records and data for the crash characteristics from crash reports.

Statistical analysis

We used binomial regression to model the risk of injury and to estimate risk differences and the number needed to treat (NNT) for selected injury risk factors among pregnant drivers who were in crashes after the 20th week of pregnancy.[102] NNTs were calculated by dividing 1 over the risk difference estimates and interpreted as, on average, the number of people who need to be treated (or “exposed” to a particular risk factor) to increase or decrease the number of injured drivers by one. We chose to estimate risk differences and NNTs because measures of absolute changes in risk are more relevant for describing public health impact than relative measures of risk.[106,107]

DAGitty software (v1.1)[101] identified the appropriate adjustment sets of covariates (Table A.3). We examined several risk factors for injury and the DAG provided different adjustment sets for each of these associations. For selected risk factors (i.e., race and Hispanic ethnicity, suspected alcohol use, belt use, vehicle speed, type, number of occupants, ambient light, crash locality, road surface, and weather), the DAG analysis identified more than one minimally sufficient set for estimating injury risks. Therefore, we conducted a sensitivity analysis to estimate risk differences for these selected injury risk factors while considering all of the adjustment sets. In the tables, we present estimates that were adjusted for sets of covariates that had none or few unmeasured variables. In the text, we present the range of estimates that were observed in the sensitivity analysis.

We considered generalized estimating equations (GEEs) to account for correlated observations among pregnant drivers in multiple crashes during the same pregnancy. However, since only a small proportion of the population was in more than one crash (2%), estimates from the GEE analysis were not noticeably different from non-GEE estimates and are not reported. We were unable to reliably identify drivers who were in multiple crashes across different pregnancies. This study was approved by the Institutional Review Board of the University of North Carolina at Chapel Hill.

Results

Study population

There were 11,052 pregnant drivers in crashes after the 20^{th} week of pregnancy in 2001-2008. High proportions of these women were 25-34 years, non-Hispanic white, educated at least through high school, married, did not use any tobacco or alcohol during pregnancy, began prenatal care before the 20^{th} week of pregnancy, and had no live births prior to the index birth (Table 5.1). The mean number of weeks of pregnancy completed by women in this cohort was 39.0 weeks (standard deviation=2.3).

Risk factors for maternal injury

The overall risk of injury was 39.9 per 100 pregnant drivers in crashes (Table 5.2). The majority of the 4,414 driver injuries were minor (n=3,899), with fewer crashes resulting in moderate (n=476), or severe (n=37) injuries. Two crashes resulted in fatalities. Pregnant drivers in crashes were at higher risk of any injury if they were 16-17 years or 18-24 years compared to 25-34 years; non-Hispanic black (adjusted risk difference, RD=7.5 to 9.0) or other non-Hispanic race (RD=4.1 to 6.0) compared to non-Hispanic white; suspected to be under the influence of alcohol (RD=1.0 to 9.6); or unbelted (RD=20.7 to 23.9). On average, for every 15 women under the influence of alcohol (NNT=15), one injury could have been prevented if they had all abstained from alcohol. For every 5 unbelted women (NNT=5), one injury could have been prevented if they had all worn belts. Risk estimates were reduced for those 35 years and older.

Injury risk was also higher if the airbag deployed (vs. no airbag), for crashes occurring at speeds of 25-45 mph or greater than 45 mph (RD=3.1 to 3.3) compared to less than 25 mph, and for serious or severe crashes with substantial vehicle damage (Table 5.3). Risk estimates were elevated for crashes in dark conditions (vs. daylight, RD=2.2 to 2.8), and reduced for crashes in urban areas (vs. mixed areas, RD =-2.3 to -2.4) (Table 5.4). Passenger cars, vehicles with 2 or more occupants, rural areas, wet roads and inclement weather had weaker positive associations with injury risk.

Discussion

We identified several characteristics that may increase a pregnant driver's risk of injury in a crash, including young age, black race, suspected alcohol use, seat belt non-use, airbag deployment, moderate or high vehicle speed, substantial vehicle damage, passenger cars, multiple occupants, dark conditions, rural areas, wet road surfaces, and inclement weather. Older age and urban areas were associated with a lower injury risk. To date, there are no other population-based studies that have examined risk factors for crash-related maternal injuries. However, there is evidence to suggest that, in general populations, several of these factors are associated with an increased risk of severe crashes. Crash-related injury is the leading cause of death among young drivers, owing to their greater involvement in serious crashes.[100] Black adults, particularly those ages 25-64, are more likely to die in crashes than white adults.[117] Risky driving behaviors, such as using alcohol and speeding, and distractions from occupants are known determinants of severe crashes.[100] In addition, rural areas have higher crash fatality rates than urban areas.[118] Other environmental factors, such as ambient light, roadways, and weather conditions, are associated with crash involvement such that inadequate visibility and impaired vehicle controllability from environmental conditions contribute to an increased crash risk.[100]

Seatbelts and airbags are effective at reducing the risk of fatal injury for most drivers.[100,119] Among pregnant women, belt use is associated with a lower risk of maternal injury and death,[20,116] but the effect of airbag deployment on maternal injury is less clear. While case reports have suggested an increased risk of maternal injury,[57,62] a more recent population-based study in Washington State did not find an increased risk of adverse maternal outcomes from airbag deployment.[4] In our study, after adjusting for crash severity (i.e., vehicle damage) and vehicle speed, crashes with deployed airbags were still more likely to result in driver injury. Residual confounding by unmeasured or poorly measured crash characteristics may explain the association between airbags and maternal injury. Although we adjusted for vehicle damage and speed in our analysis, there are other crash severity measurements associated with airbag deployment and injury risk that were not measured, including the angle of impact and change in velocity (i.e., delta-V). The association between airbags and injury may be modified by seat belt use. However, a valid estimate of the causal effect of airbags on injury and a reliable belt use measure are needed to adequately assess effect measure modification.

Strengths and limitations

Due to the nature of data collection and reporting for vital records and the high frequency of unrecognized and unreported fetal losses early in pregnancy, we did not examine injuries among pregnant drivers in crashes before the 20th week of pregnancy. We were also unable to identify pregnant drivers in crashes who moved out of NC, out-of-state crashes among pregnant NC drivers, and pregnant driver crashes that did not link to vital records.

There is the potential for misclassification of key measures from the linked data sources. An accurate estimate of gestational age is important for determining crash involvement in pregnancy. However, the LMP and clinical estimates obtained from vital records are susceptible to error.[98,111-113] We attempted to minimize this by using the same method that is used by the National Center for Health Statistics for estimating gestational age in U.S. vital statistics.[98,99] This method relies mostly on LMP-based estimates with replacement of unreasonable or missing values by clinical or physician's estimates. Previous studies have also found that behavioral risk factors reported in NC birth records (e.g., prenatal tobacco and alcohol use) are not reliable.[114,115] As such, one must be cautious when interpreting results adjusted for these behavioral measures.

In addition to vital records data, accurate and reliable data from crash reports are essential for obtaining valid estimates of injury risk. Police-reported information for vehicle speed[120] and belt use[121] is known to be unreliable, thus inclusion of these variables in our regression models may distort the association between crash characteristics and the risk of injury. Police-reported injury status based on the five-point KABCO scale may also be unreliable, such that police may correctly classify fatal injuries, but misclassify non-fatal injuries as either occurring when there is no injury present, or as being more severe than they actually are.[120,122,123] Less visible internal injuries (e.g., uterine or placental injury) may also be underreported. The inclusion of additional data sources with detailed injury information (e.g., emergency medical services, emergency department, and inpatient data) would provide useful information for validating injury status. Similar to previous studies,[3,4,7] we lack information on delta-V which could provide a more valid measure of crash severity.

Despite the limitations, this study has several unique strengths, including the large size and diversity of the cohort, the use of probabilistic linkage methodology to ascertain pregnant driver crashes that are not otherwise documented, and the examination of robust crash characteristics from NC's comprehensive crash reports. This is also the first study that has examined several types of risk factors for crash-related maternal injuries. There is room for improvement of modifiable risk factors to minimize pregnant drivers' risk of injuries. If more pregnant drivers wore seatbelts or engaged in safer driving behaviors, such as not drinking alcohol, then their injury risk could be reduced.

Tables

Table 5.1. Characteristics of pregnant drivers in crashes after the 20th week of pregnancy in North Carolina (N=11,052), 2001-2008.

	No. of Pregnant Drivers in Crashes	%
Maternal age, years		
16-17	181	2
18-24	4,481	41
25-34	5,203	47
35+	1,187	11
Missing	0	0
Race & Hispanic ethnicity		
Non-Hispanic white	6,253	57
Non-Hispanic black	3,410	31
Hispanic	945	9
Non-Hispanic other	437	4
Missing	7	<1
Maternal education		
Less than high school	1,791	16
High school graduate	3,753	34
Some college	2877	26
College graduate	2620	24
Missing	11	<1
Marital status		
Married	6,117	55
Not married	4,934	45
Missing	1	<1
Tobacco use during pregnancy		
Yes	1,485	13
No	9,553	87
Missing	14	<1
Alcohol use during pregnancy		
Yes	44	1
No	10,993	99
Missing	15	<1
Prenatal care before the 20th week		
Yes	10,499	96
No	456	4
Missing	97	<1
Parity		
1	4,475	41

2	3,735	34
≥3	2,837	26
Missing	5	<1

Table 5.2. Driver characteristics and the risk of injury among pregnant drivers in crashes after the 20th week of pregnancy in North Carolina (N=11,052), 2001-2008.

	No. of pregnant drivers in crashes	No. of injured pregnant drivers	Injury risk[a]	Risk Difference	NNT	95% CI
Overall	11,052	4,414	39.9			
Maternal age, years[b]						
16-17	181	75	41.4	4.1	(24)	-3.2, 11.5
18-24	4,481	1,980	44.2	6.7	(15)	4.7, 8.7
25-34	5,203	1,946	37.4	0		Reference
35+	1,187	413	34.8	-2.5	(-39)	-5.6, 0.5
Missing	0	0				
Race & Hispanic ethnicity[c]						
NH white	6,253	2,311	37.0	0		Reference
NH black	3,410	1,565	45.9	9.0	(11)	6.9, 11.1
Hispanic	945	349	36.9	0.6	(178)	-2.9, 4.0
NH other	437	186	42.6	5.7	(18)	0.8, 10.5
Missing	7	3				
Gestational age at crash[d]						
20-27	5,027	1,980	39.4	0		Reference
28-32	2,950	1,192	40.4	0.9	(113)	-1.5, 3.2
33-36	2,034	821	40.4	0.8	(120)	-1.9, 3.5
37+	1,041	421	40.4	1.1	(94)	-2.5, 4.6
Missing	0	0				
Suspected alcohol use at crash[c]						
Yes	47	23	48.9	6.9	(15)	-7.3, 21.0
No	11,005	4,391	39.9	0		Reference
Missing	0	0				
Seat belt use[e]						
None	165	102	61.8	20.7	(5)	13.1, 28.2
Belt	10,680	4,240	39.7	0		Reference
Missing	207	72				

Abbreviations: NNT, number needed to treat (1/risk difference); CI, confidence interval

[a]Unadjusted injury risk per 100 pregnant drivers in crashes

[b]Adjusted for gestational age at the time of crash, alcohol use during pregnancy, vehicle speed at impact, belt use

[c]Adjusted for gestational age at the time of crash, maternal age, parity, prenatal care, tobacco use during pregnancy, alcohol use during pregnancy, belt use

[d]Adjusted for alcohol use during pregnancy, vehicle speed at impact, belt use

[e]Adjusted for gestational age at the time of crash, maternal age, parity, prenatal care, tobacco use during pregnancy, alcohol use during pregnancy

Table 5.3. Vehicle characteristics and the risk of injury among pregnant drivers in crashes after the 20th week of pregnancy in North Carolina (N=11,052), 2001-2008.

	No. of pregnant drivers in crashes	No. of injured pregnant drivers	Injury risk[a]	Risk Difference	NNT	95% CI
Airbag deployment[b]						
No air bag	1,864	817	43.8	0		Reference
Not deployed	8,007	2,710	33.9	-8.3	(-12)	-10.9, -5.7
Deployed	1,095	851	77.7	21.1	(4.7)	17.4, 24.8
Missing	86	36				
Speed at impact[c]						
<25 mph	5,795	2,064	35.6	0		Reference
25-45 mph	3,427	1,637	47.8	2.8	(35)	0.7, 4.9
>45 mph	581	299	51.5	3.1	(33)	-0.7, 6.9
Missing	1,249	414				
Vehicle damage severity[d]						
Damage <3	7,887	2,575	32.7	0		Reference
Damage ≥ 3	3,165	1,839	58.1	17.9	(5.6)	15.7, 20.2
Missing	0	0				
Vehicle type[e]						
Passenger car	10,971	4,387	40.0	6.9	(15)	-3.8, 17.6
Other	81	27	33.3	0		Reference
Missing	0	0				
Number of occupants[e]						
1 (driver)	6,504	2,535	39.0	0		Reference
2	2,640	1,098	41.6	1.8	(56)	-0.6, 4.2
3+	1,908	781	40.9	1.0	(97)	-1.7, 3.8
Missing	0	0				

Abbreviations: NNT, number needed to treat (1/risk difference); CI, confidence interval; mph, miles per hour

[a]Unadjusted injury risk per 100 pregnant drivers in crashes

[b]Adjusted for crash severity, vehicle speed at impact

[c]Adjusted for airbag deployment, gestational age at the time of crash, maternal age, parity, prenatal care, tobacco use during pregnancy, alcohol use during pregnancy, crash severity

[d]Adjusted for airbag deployment, vehicle speed at impact

[e]Adjusted for gestational age at the time of crash, maternal age, parity, prenatal care, tobacco use during pregnancy, alcohol use during pregnancy, vehicle speed at impact

Table 5.4. Environmental characteristics and the risk of injury among pregnant drivers in crashes after the 20th week of pregnancy in North Carolina (N=11,052), 2001-2008.

	No. in crashes	No. injured	Injury risk[a]	Risk Difference	NNT	95% CI
Ambient light[b]						
Daylight	8,908	3,556	39.9	0		Reference
Dark	2,130	854	40.1	2.2	(45)	-0.3, 4.8
Missing	14	4				
Crash locality[b]						
Rural (<30% developed)	2,304	950	41.2	0.1	(2091)	-3.3, 3.4
Mixed (30-70% developed)	1,722	735	42.7	0		Reference
Urban (>70% developed)	7,026	2,729	38.8	-2.3	(-44)	-5.0, 0.4
Missing	0	0				
Road surface[b]						
Dry	9,019	3,556	39.4	0		Reference
Wet	1,856	798	43.0	1.9	(53)	-0.7, 4.5
Snow or Ice	136	47	34.6	-5.0	(-20)	-13.2, 3.3
Other (sand, gravel, oil)	12	7	58.3	10.7	(9.4)	-15.3, 36.6
Missing	29	6				
Weather condition[b]						
Clear	7,835	3,084	39.4	0		Reference
Cloudy	2,160	881	40.8	-0.04	(-2402)	-2.5, 2.4
Rain or Snow	1,047	446	42.6	1.8	(55)	-1.5, 5.2
Other (fog, smoke, wind)	10	3	30.0	-2.6	(-39)	-34.5, 29.4
Missing	0	0				

Abbreviations: NNT, number needed to treat (1/risk difference); CI, confidence interval; mph, miles per hour
[a]Unadjusted injury risk per 100 pregnant drivers in crashes
[b]Adjusted for gestational age at the time of crash, maternal age, parity, prenatal care, tobacco use during pregnancy, alcohol use during pregnancy, vehicle speed at impact

VI. RESULTS: MOTOR VEHICLE CRASHES AND ADVERSE PREGNANCY OUTCOMES AMONG PREGNANT DRIVERS IN NORTH CAROLINA

Introduction

Trauma during pregnancy is a leading cause of maternal and fetal morbidity and mortality. In the United States, it is estimated that up to 7% of all pregnancies are complicated by traumatic events.[10] Blunt abdominal trauma is of particular concern to a pregnant women and her fetus since it can directly and indirectly harm fetal organs as well as shared maternal and fetal organ systems. Direct fetal injury, although rare, includes splenic rupture, skull fractures and brain injury; direct harm to shared organs and systems includes placental abruption, uterine rupture, and amniotic rupture.[15,19,25] Fetuses may also be vulnerable to indirect effects of trauma, such as an increased risk of spontaneous preterm birth or low birth weight resulting from premature labor, with consequences that can have long term effects.[10,15]

Motor vehicle crashes are responsible for most traumatic events resulting in hospitalization during pregnancy, but little is known about the effect of crashes on fetal morbidity not resulting in hospitalization and fetal mortality.[8-12,15] While several case reports have quantified the effect of crashes on fetal outcomes,[69,71,73] population-based studies are lacking, largely due to the lack of standardized reporting of crash-related fetal injury. State crash reports do not routinely report pregnancy status or classify fetal deaths as fatal injuries resulting from crashes.

A few studies have addressed these limitations by linking vital records and crash reports to examine the association between police-reported crashes and adverse fetal outcomes,[3,4,6] but only one of these studies compared fetal outcomes for pregnant women in crashes to those not in crashes.[3] This study was limited in its ability to detect associations given the relatively small study population (n=325,349 births) and small number of outcomes (n=8,983 births exposed to crashes) observed during the study period. Large sample sizes are needed to better understand the effect of crashes on pregnancy outcomes. Our objective was to estimate the association between crashes and selected pregnancy outcomes using a large cohort of pregnant women in North Carolina (NC).

Methods

Study population

We conducted a retrospective cohort study of 878,546 pregnant NC residents, aged 16-46 years, who reached the 20th week of pregnancy and delivered a live or stillborn singleton infant between January 1, 2001 and December 31, 2008. These women completed a total of 115,797,259 pregnancy days following the 20th week of pregnancy. They were identified from live birth and fetal death records (n=993,274). Pregnancies that did not reach the 20th week were excluded because fetal deaths occurring before 20 weeks are not reported in NC vital records. We excluded records for women aged less than 16 years (n=7,075) since driver crashes in this pre-licensure age group are rare. We also excluded records for women older than 46 years at delivery (n=237) and those with multiple gestation deliveries (n=33,360) since older maternal age and multifetal gestation are associated with a higher risk of non-trauma-related adverse pregnancy outcomes. Records missing data for at least one of the following: mother's age (n=73), multiple gestation status (n=91), or gestational age at delivery (n=481), were removed. There were 73,453 pregnant women who did not meet the cohort definition for this study.

To determine if a motor vehicle crash occurred during pregnancy, vital records were probabilistically linked to state crash records for licensed female drivers using mother's first and last name, date of birth, race, and residential county. We were unable to link to passengers because identifying information was not available from the crash reports. This linkage was performed using LinkSolv generalized linkage software (Strategic Matching Inc., Morrisonville, NY, 2009). Detailed information about the linkage methodology is described elsewhere (pages 59-60).

Measures

Motor vehicle crashes

A motor vehicle crash was defined as a crash that involved a NC licensed female driver of a motor vehicle or passenger truck. Crash reports were completed by police if the crash occurred on a public roadway and resulted in a fatality or non-fatal personal injury to any vehicle occupant, total property damage greater than $1000, or property damage of any amount to a vehicle seized. A woman could be a driver in more than one crash during the same pregnancy. We classified motor vehicle crashes according to the total number of crashes a woman experienced during each pregnancy (i.e., 0, 1 or 2 or more crashes). We were unable to identify drivers who were in multiple crashes across different pregnancies.

Fetal outcomes

Preterm birth was defined as a live birth that occurred between 20 and 37 weeks of gestation. Live births occurring before the 20th week (n=455) were excluded. To determine if a birth was preterm, we estimated gestational age using the method that is used by the National Center for Health Statistics for estimating gestational age in U.S. vital statistics.[98,99] This methodology relies primarily on the self-reported date of the last menstrual period (LMP). For records that were missing the date of LMP or had an implausible gestational age when compared to birth weight, the clinical estimate was used (n=51,593 or 5.2%). If records were missing the LMP-based and clinical estimates, the physician's estimate (estimated from pregnancy history, early ultrasound, or examination of the stillborn infant), which is only reported on fetal death records, was used for stillbirths (n=531, <0.1%). Records missing all values were excluded (n=481, <0.1%).

Stillbirth was defined as an intrauterine death that occurred after the 20th week of gestation. Stillbirth status, excluding induced abortions, was determined by hospital administrators, physicians, and medical examiners.

Obstetric conditions

Obstetric complications, as recorded on the live birth and fetal death certificates, were placental abruption (i.e., separation of the placenta from the uterus during pregnancy) and premature rupture of the membranes (PROM) (i.e., spontaneous rupture of the amniochorionic membrane occurring 12 or more hours before the onset of labor).

Covariates

Several potential confounders of the association between crashes and the rate of adverse pregnancy outcomes were selected for examination using a directed acyclic graph (DAG) based on a review of the literature (Table A.1).[3,5] These covariates included gestational age, maternal age, maternal race and Hispanic ethnicity (categorized as non-Hispanic white, non-Hispanic black, other non-Hispanic race, and Hispanic), maternal education, prenatal tobacco use, prenatal alcohol use, trimester of prenatal care initiation, and parity (defined as the total number of live births including the index birth). Data for these covariates were obtained from live birth and fetal death certificates.

Statistical analysis

We used Poisson regression to estimate rate ratios for the associations between crashes and preterm birth, stillbirth, placental abruption, and PROM. Person-time at risk for the cohort was defined as pregnancy days completed after the 20th week. The number of crashes during pregnancy was modeled as a time-dependent exposure, thus an individual woman could contribute time to more than one crash exposure category if she was a driver in more than one crash during the same pregnancy.

Incidence rates were defined as the number of events (i.e., preterm birth, stillbirth, placental abruption, or PROM) divided by the total number of days of pregnancy completed after the 20th week, within each crash exposure category. For the estimation of preterm birth rates, only live births (numerator) and pregnancy days (denominator) occurring between 20 and 37 weeks of pregnancy were counted. Estimated rates for all other outcomes included all events and days that occurred between the 20th week and the completion of the pregnancy.

We used DAGitty software (v1.0)[101] to identify the appropriate sets of confounders for adjustment in the analysis of each exposure-outcome association (Table A.4). There were two or more minimally sufficient adjustment sets that were identified for estimating the rate of placental abruption and PROM by crash involvement. We conducted a sensitivity analysis to estimate rate ratios for these two outcomes while considering all of the adjustment sets. In the tables, we present estimates that were adjusted for covariates that had few unmeasured variables. In the text, we present the range of estimates that were observed in the sensitivity analysis. This study was approved by the Institutional Review Board at the University of North Carolina at Chapel Hill.

Results

Study Population

There were 25,168 pregnant NC women who were drivers involved in at least one crash during pregnancy in 2001-2008 (2.9%); 24,399 women were drivers in only one crash (2.8%) and 769 were in two or more crashes during the same pregnancy (0.1%). A high proportion of pregnancy-time following the first crash was among women who were 25-34 years, non-Hispanic white, high school graduates, married, non-tobacco users, non-drinkers, early initiators of prenatal care, and primiparas (Table 6.1). The distribution of pregnancy-time following the second or subsequent crashes was similar for most maternal characteristics, with the exception of age and marital status, where a high proportion of pregnancy-time was among women who were 18-24 years and unmarried.

Pregnancy outcomes

Fetal outcomes

Between 2001 and 2008, there were a total of 100,515 preterm births (11.4%) and 5,447 stillbirths (0.6%) that occurred among pregnant women in the study population (Table 6.2). Pregnant drivers had elevated rates of preterm birth following their first crash, compared to no crashes. The highest rates were observed following their second or subsequent crashes. Each additional crash (i.e., an increase of one crash in the exposure measure) was associated with an increased rate of preterm birth (RR=1.07, 95% CI 1.03, 1.11). Similarly, pregnant drivers had higher rates of stillbirth following their first crash, and even higher rates following their second or subsequent crashes, compared to no crashes. The estimated rate ratio of stillbirth for each additional crash was 1.23 (95% CI 1.05, 1.44).

Obstetric conditions

There were 5,866 placental abruption events (0.7%) and 19,721 PROM events (2.2%) that occurred between 2001 and 2008 (Table 6.3). Pregnant drivers had higher rates of placental abruption (adjusted rate ratio, RR, 1.11 to 1.14) and PROM (RR=1.09 to 1.13) following their first crash, compared to no crashes. The highest rates of placental abruption (RR=1.89 to 2.20) and PROM (RR=1.34 to 1.48) were observed following their second or subsequent crashes, compared to no crashes. For each additional crash, the estimated rate ratios for placental abruption and PROM were 1.19 (95% CI 1.04, 1.37) and 1.14 (95% CI 1.05, 1.23), respectively.

Discussion

In this study, 2.9% of pregnant women who delivered a live or stillborn singleton infant after the 20th week were drivers in at least one crash during pregnancy. Of the women who were pregnant drivers in crashes, 3.1% were in more than one crash during the same pregnancy. Crashes involving a pregnant driver were associated with elevated rates of adverse pregnancy outcomes (preterm birth, stillbirth, placental abruption, and PROM). The rates of these outcomes increased as the number of crashes increased.

Only one previous linkage study has examined the association between police-reported motor vehicle crashes (any vs. none) and adverse pregnancy outcomes.[3] This study found a weak, positive association between crashes and the risk of preterm birth (odds ratio, OR, 1.02, 95% CI 0.94, 1.11) and no association with placental abruption (OR=1.00, 95% CI 0.81, 1.24).[3] Positive associations were also observed for other pregnancy outcomes, including low birth weight (OR=1.03, 95% CI 0.94, 1.14) and fetal distress (OR=1.09, 95% CI 0.98, 1.21).[3] The Utah researchers did not report the association between crashes and the risk of stillbirth or PROM. The stronger associations observed in our study may be due to the overall higher rate of adverse pregnancy outcomes among pregnant women in North Carolina as compared to Utah.[124,125]

The associations we observed between crashes and adverse pregnancy outcomes may be modified by crash severity and belt use. A previous epidemiological study found that pregnant women in Washington State (WA) who were hospitalized with severe crash-related injuries were at increased risk of several adverse outcomes (i.e., preterm delivery, fetal death, fetal distress, and placental abruption), as compared to pregnant women not in crashes.[5] Another study conducted in WA evaluated the effect of belt use on pregnancy outcomes and found that unbelted pregnant women in crashes were at higher risk of delivering a low birth weight and/or stillborn infant, compared to belted women.[6] Similar, but weaker, associations between belt use and pregnancy outcomes were found among pregnant women in Utah.[3] More research is needed to further extend these results.

This study has several limitations. There is the potential for misclassification of pregnancy outcomes as determined from vital records data. LMP-based and clinical estimates of gestational age are unreliable.[98,111-113] We addressed this limitation by replacing implausible and missing LMP-based measures with clinical estimates, but misclassified estimates likely remain for some births. The validity and reliability of reported labor and delivery complications, including placental abruption and PROM, are also questionable.[114,115] These obstetric conditions are often reported with knowledge of the birth outcome, thus over-reporting in the presence of adverse outcomes (e.g., stillbirth) is possible. In the absence of medical records, we were unable to validate these outcomes. Behavioral risk factors, including prenatal tobacco and alcohol use, may also be unreliable.[114,115] Adjustment for these poorly measured confounders in our models may distort the association between crashes and adverse pregnancy outcomes.

Due to the lack of information regarding early fetal losses and terminations in vital records, we were unable to observe all crashes and fetal outcomes occurring before the 20th week of pregnancy. We were also unable to observe out-of-state crashes among pregnant NC drivers and crashes involving pregnant passengers in NC. The lack of data on passengers likely had no effect on our estimates since most pregnant women are involved in crashes as drivers (70%) rather than as passengers (30%).[1] Additional studies utilizing datasets with detailed information on passengers would be beneficial to examine the effect of pregnant passenger crashes on adverse pregnancy outcomes. These studies could also be used to examine pregnant occupant seating positions to determine if there is an optimal seating location for minimizing the effect of crashes on adverse outcomes.

In our study, we did not distinguish between immediate and delayed effects of crashes on the rate of adverse pregnancy outcomes. Crashes occurring well before delivery may not be as strongly associated with some outcomes (e.g., premature labor, stillbirth), as compared to crashes occurring immediately before delivery. Future studies assessing the time of the crash in relation to delivery may provide additional insight regarding the association between crashes and adverse pregnancy outcomes.

This study also has several strengths. To date, this is the largest state-based study that has examined the effects of crashes during pregnancy in a cohort of pregnant women. This is also the first study to examine dose-response effects of increasing number of crashes during pregnancy on the rate of adverse pregnancy outcomes. Probabilistic record linkage methodology allowed us to ascertain both hospitalized and non-hospitalized pregnant driver crashes, thus allowing a population-based approach to examining the effect of crashes on fetal outcomes.

This study highlights the importance of crashes during pregnancy and their effect on fetal outcomes and obstetric conditions. Clinicians should be aware of the effects of crashes during pregnancy and should advise pregnant women about the risk of being in a crash and about the short and long term consequences that crashes can have on their pregnancy. Additional large cohort studies of pregnant women are needed to further examine the effect of crashes on adverse fetal outcomes. In particular, studies exploring the timing of crashes relative to delivery and assessing the effect of seat belts and airbags on adverse pregnancy outcomes is warranted. A better understanding of the circumstances surrounding crashes during pregnancy and how vehicle design and safety features may play a role in adverse pregnancy outcomes is needed to develop effective strategies for prevention.

Tables

Table 6.1. Maternal characteristics and pregnancy days completed after the 20th week, by crash involvement, among pregnant drivers in North Carolina, 2001-2008.

	No Motor Vehicle Crashes During Pregnancy		First Motor Vehicle Crash During Pregnancy		Second or Subsequent Motor Vehicle Crashes During Pregnancy	
	Pregnancy days	%	Pregnancy days	%	Pregnancy days	%
Maternal age, years						
16-17	3,355,531	3	41,315	2	1,424	2
18-24	39,765,905	35	1,121,819	43	35,226	53
25-34	56,434,076	50	1,173,630	45	24,543	37
35+	13,583,100	12	255,832	10	4,858	7
Missing	0	0	0	0	0	0
Maternal race & Hispanic ethnicity						
Non-Hispanic white	65,297,653	58	1,486,112	57	31,913	48
Non-Hispanic black	25,156,827	22	787,850	30	26,176	40
Hispanic	17,740,392	16	219,940	8	4,895	7
Non-Hispanic other	4,817,986	4	97,708	4	3,067	5
Missing	125,754	<1	986	<1	0	0
Gestational age, weeks						
20-27	48,023,344	42	924,075	36	19,791	30
28-32	29,516,522	26	700,060	27	17,669	27
33-36	22,379,033	20	589,464	23	17,128	26
37+	13,219,713	12	378,997	15	11,463	17
Missing	0	0	0	0	0	0
Maternal education						
Less than high school	25,292,305	22	442,135	17	12,099	18
High school graduate	32,822,304	29	896,299	35	26,583	40
Some college	24,856,817	22	685,269	26	18,649	28
College graduate	29,950,877	27	565,743	22	8,534	13
Missing	216,309	<1	3,150	<1	186	<1
Marital status						
Married	71,243,242	63	1,384,998	53	26,311	40
Not married	41,891,307	37	1,207,478	47	39,740	60
Missing	4,063	<1	120	<1	0	0
Prenatal tobacco use						
Yes	13,278,892	12	360,853	14	10,254	16
No	99,740,283	88	2,229,106	86	55,760	84
Missing	119,437	<1	2,637	<1	37	<1

Prenatal alcohol use						
Yes	530,507	1	10,981	1	0	0
No	112,480,405	99	2,579,104	99	66,014	100
Missing	127,700	<1	2,511	<1	37	<1
Prenatal care initiation						
1st Trimester	93,999,726	84	2,171,528	84	52,771	80
2nd Trimester	14,725,518	13	335,291	13	10,816	17
3rd Trimester	1,056,294	1	23,388	1	615	1
None	2,509,613	2	41,982	2	1,304	2
Missing	847,461	<1	20,407	<1	545	<1
Parity						
1	46,531,820	41	1,104,430	43	28,053	42
2	37,865,118	33	838,154	32	20,160	31
≥3	28,690,826	25	648,659	25	17,838	27
Missing	50,848	<1	1,353	<1	0	0

Table 6.2. Rates and adjusted rate ratios for preterm birth and stillbirth, by crash involvement, among pregnant drivers in North Carolina, 2001-2008.

	Preterm birth					Stillbirth				
	Preterm births	Pregnancy days	Rate[a]	Rate ratio[b]	95% CI	Still births	Pregnancy days	Rate[a]	Rate ratio[b]	95% CI
Crashes during pregnancy										
No crashes	97,737	99,918,899	97.8	1.00	Reference	5,305	113,138,612	4.7	1.00	Reference
First crash	2,692	2,213,599	121.6	1.07	1.03,1.11	128	2,592,596	4.9	1.06	0.88, 1.27
Second crash	86	54,588	157.5	1.16	0.94, 1.44	14	66,051	21.2	4.68	2.77, 7.91

Abbreviations: CI, confidence interval

[a]Unadjusted rates per 100,000 pregnancy days

[b]Adjusted for gestational age, maternal age, parity, prenatal care, prenatal tobacco use, prenatal alcohol use

Table 6.3. Rates and adjusted rate ratios for placental abruption and premature rupture of the membranes, by crash involvement, among pregnant drivers in North Carolina, 2001-2008.

	Placental abruption					Premature rupture of the membranes				
	Placental abruptions	Pregnancy days	Rate[a]	Rate ratio[b]	95% CI	Premature ruptures of the membranes	Pregnancy days	Rate[a]	Rate ratio[b]	95% CI
Crashes during pregnancy										
No crashes	5,680	113,138,612	5.0	1.00	Reference	19,126	113,138,612	16.9	1.00	Reference
First crash	175	2,592,596	6.7	1.14	0.98, 1.33	574	2,592,596	22.1	1.13	1.04, 1.22
Second crash	11	66,051	16.7	2.20	1.18, 4.09	21	66,051	31.8	1.48	0.96, 2.27

Abbreviations: CI, confidence interval

[a]Unadjusted rates per 100,000 pregnancy days

[b]Adjusted for gestational age, maternal age, parity, prenatal care, prenatal tobacco use, prenatal alcohol use

VII. DISCUSSION

Summary of findings

This dissertation research sought to examine the effect of motor vehicle crashes on adverse maternal and fetal outcomes among pregnant drivers in North Carolina. The three main objectives were to: 1) estimate the risk and describe the risk factors for being a pregnant driver in a motor vehicle crash after the 20th week of pregnancy in NC; 2) estimate the risk and describe the risk factors for sustaining crash-related maternal injuries among pregnant NC drivers who were in crashes after the 20th week of pregnancy; and 3) examine the association between motor vehicle crashes involving a pregnant NC driver and the rates of preterm birth, stillbirth, placental abruption, and PROM. These objectives were addressed using linked vital records and crash reports from NC between 2001 and 2008.

Overall, we found that 2.9% of pregnant women in our study population were drivers in at least one crash during pregnancy. As compared to previous state-level linkage studies that estimated pregnancy crash risks ranging from 1.0% in Washington State (WA)[4] to 2.8% in Utah (UT),[3] NC appears to have the highest reported pregnant driver crash risk. We also found that the risk of being a pregnant driver in a crash was the lowest during the last few weeks of pregnancy. This is likely due to a lower frequency of driving during that time. Similar to risk factors identified in prior studies,[3,5] pregnant NC women were at greatly increased risk of being a driver in a crash if they were younger, non-Hispanic black, less educated, unmarried, and used tobacco during pregnancy. These women were also at higher risk if they were multiparous and at lower risk if they were older or Hispanic.

In addition to identifying crash determinants, we found several maternal, vehicle, and environmental characteristics that were associated with an increased risk of crash-related injury during pregnancy. Among pregnant drivers who were in crashes, those who were not wearing seat belts or were in crashes severe enough for substantial vehicle damage or airbag deployment, were at greatly increased risk of injury. Pregnant drivers in crashes who were younger, non-Hispanic black, or under the influence of alcohol had considerable, but lesser, degrees of increased injury risk. Although no previous studies have examined risk factors for crash-related maternal injuries, there is evidence suggesting that many of these factors (i.e., young age,[100] black race,[117] alcohol use[100]) are associated with severe crashes in the general population. Our results are consistent with previous studies that found seat belts to be associated with a lower risk of maternal injury.[20,116] The effect of airbags on maternal injury remains unclear.

We also found an association between motor vehicle crashes and the rate of several adverse pregnancy outcomes. Pregnant drivers had elevated rates of preterm birth, stillbirth, placental abruption, and PROM following their first crash, compared to no crashes. The rates of these outcomes were even higher following their second or subsequent crashes. In contrast to the only other study[3] that has examined the association between police-reported crashes and adverse pregnancy outcomes (in Utah), we were able to detect a stronger association between crashes and selected outcomes (i.e., preterm birth and placental abruption). The Utah researchers did not report the association between crashes and the risk of stillbirth or PROM. No prior study has examined the dose-response relationship between crashes during pregnancy and adverse pregnancy outcomes.

Public health implications

The results from this dissertation research have several implications for public health and clinical practice. Based on estimates from four states that have used linked vital records and crash reports to examine crashes during pregnancy, as many as 2.9% of pregnant women are involved as drivers in crashes. The pregnant driver crash risk may be even higher in other states, particularly those with higher crash risks among reproductive-aged women (e.g., Mississippi, Montana, Wyoming).[7] To further increase awareness of this important public health issue and to identify states with high pregnancy-related crash risks, we must improve our ability to track crashes and injuries during pregnancy through ongoing statewide surveillance. All states routinely collect vital records and crash data, yet very few have linked these data sources to monitor this issue and none monitor it routinely. Several states have already linked crash reports to other injury outcome databases through the Crash Outcome Data Evaluation System (CODES),[126] but only one of these states has added live birth and fetal death records to its existing linkage. In the absence of a reliable data system for tracking crashes and crash-related injuries during pregnancy, more states should adapt pregnancy-related crash surveillance systems by utilizing record linkage procedures.

Additionally, we identified factors that may increase a pregnant woman's risk of being a driver in a crash (i.e., young age, black race, low education, unmarried status, prenatal tobacco use). This information can be used to develop crash prevention strategies that are targeted towards women with these characteristics. We also found that the risk of being a driver in a crash is higher in the second trimester and lower at the end of the third trimester which suggests that women may not be driving later in pregnancy. Pregnant women can be encouraged to decrease their crash risk by driving less frequently. Little is known about driving patterns during pregnancy and there are currently no known attempts at interventions to reduce driving frequency among pregnant women. More research is needed to quantify how often pregnant women drive and how much time they spend driving. Additional information on driving frequency and patterns would enable the estimation of more valid crash risks, particularly those at different weeks of pregnancy.

The identification of modifiable risk factors to minimize the risk of crash-related maternal injuries has important implications. Given the evidence that wearing a seatbelt can reduce the risk of maternal injury, pregnant women should be encouraged to wear belts and wear them properly while in a motor vehicle. Adoption of primary seat belt laws and enforcement of existing mandatory seat belt laws may help to ensure that pregnant drivers are belted. In addition to encouraging belt use, clinicians should remind pregnant women that using alcohol is not only harmful to their fetus, but it can also increase their risk of injury in a crash. Greater awareness and education for safe driving behaviors during pregnancy is needed, particularly among women who are at highest risk of being pregnant drivers in crashes and of sustaining crash-related injuries (i.e., young, black women).

Finally, motor vehicle crashes, especially multiple crashes, were found to increase the rate of adverse pregnancy outcomes. Clinicians should be aware of the effects of crashes during pregnancy and able to advise women about the risk of being a driver in a crash and about the short and long term consequences that crashes can have on their pregnancy. Additional studies should assess the impact of vehicle safety devices on these outcomes. Overall, more prevention efforts are needed, either at the individual level (e.g., behavior modification, use of personal safety devices), vehicle level (e.g., vehicle design modification, development of crash protection systems for pregnant women), or through legislation (e.g., enforcement of seat belt laws). These strategies, together with improved surveillance, can improve motor vehicle safety for pregnant women and their fetuses.

Strengths and limitations

To date, this is the largest state-based study that has examined the effects of crashes during pregnancy on adverse maternal and fetal outcomes in a large and diverse cohort of pregnant women enumerated over an eight-year study period. The use of probabilistic record linkage methodology allowed us to ascertain both hospitalized and non-hospitalized police-reported pregnant driver crashes that are not otherwise documented. This is the first study to examine several types of risk factors for crash-related maternal injuries and to examine the dose-response effects of increasing number of crashes during pregnancy on adverse pregnancy outcomes.

A key limitation of this research is that all data were obtained from administrative databases and the validity and reliability of several measures from these datasets are questionable. For all specific aims, an accurate estimate of gestational age was important for determining crash involvement during pregnancy; for Specific Aim 3, gestational age was important for enumerating the pregnancy days at risk as well as for defining preterm birth. It is known that LMP-based and clinical estimates of gestational age from vital records are susceptible to error.[98,111-113] Therefore, based on methods used by the National Center for Health Statistics, we created a composite measure of gestational age that combined LMP-based and clinical measures to minimize the potential for error.[98,99] However, despite our efforts, misclassified estimates may still remain for some records.

Prior studies have assessed the reliability of maternal demographics, health behaviors, and pregnancy events as recorded on birth certificates.[114,115] These studies found that while maternal demographics were highly reliable, reported labor and delivery complications (e.g., placental abruption and PROM) and behavioral measures (e.g., prenatal tobacco and alcohol use) were not very reliable.[114,115] Therefore, the obstetric conditions assessed in Specific Aim 3 may be over-reported, especially in the presence of certain outcomes (e.g., stillbirth). For all specific aims, adjustment for poorly measured behavioral characteristics in our models may have distorted the association between crashes and adverse outcomes. In the absence of medical records, we were unable to validate any of these measures. We were also unable to measure socioeconomic status or other social and behavioral factors that may confound several of the associations that were estimated. As such, we urge caution when interpreting these results.

Accurate and reliable data from crash reports are also necessary for obtaining valid estimates in our study, particularly the injury risk estimates in Specific Aim 2. Prior studies found that police-reported injury status based on the five-point KABCO scale[97] were unreliable, especially for non-fatal injuries which were often misclassified as being more severe than they actually were.[120,122,123] We were unable to obtain data from emergency medical services or hospital records to validate injury status. In addition, police-reported vehicle speed[120] and belt use[121] are known to be unreliable. Based on a prior validation study, we expected that belt use was over-reported for non-severe crashes and underreported for severe crashes.[121] We also lacked information on the most valid measure of crash severity, i.e., the change in velocity at the time of impact (or delta-V).

Our study was also limited by our inability to observe all pregnancies and crashes that occurred during the study period. Because of the lack of information for early fetal losses and terminations in vital records, we were unable to observe pregnancies that ended before the 20th week. We were also unable to observe women who moved out of NC during pregnancy, out-of-state crashes among pregnant NC drivers, and pregnant driver crashes that did not link to vital records. Overall, many of these events are rare and should not bias our results. In addition, although most pregnant women are involved in crashes as drivers (70%),[1] like most prior studies,[3,6,7] we could not identify women in our study population who were pregnant passengers in crashes due to the lack of identifying information in the crash reports. There is the possibility that our rate estimates (in Specific Aim 3) are biased if women at higher risk of adverse pregnancy outcomes are more (or less) likely to travel as drivers of motor vehicles, instead of as passengers.

Specific Aim 1 was limited by our inability to quantify the amount of time women spent driving a motor vehicle during pregnancy and we could not include this information in the denominator of our crash risk estimates. We instead estimated the number of women at risk of being a driver in a crash among all pregnant women who completed the 20th week of pregnancy, regardless of how much they drove. Our crash risk estimates may be biased if they are associated with driving time.

Conclusions

The effect of crashes on adverse maternal and fetal outcomes among pregnant drivers is an important public health issue affecting thousands of pregnant women each year, especially those in North Carolina. Young, black, unmarried pregnant women who use tobacco or have not obtained a college degree are at particularly high risk of being drivers in crashes during pregnancy. These crashes are not only associated with an increased risk of maternal injury, but they are also associated with elevated rates of preterm birth, stillbirth, placental abruption and PROM. Rates of adverse pregnancy outcomes are especially high following the second or subsequent crashes while driving during pregnancy. The results from this study suggest that seat belt use and alcohol nonuse can minimize the risk of crash-related maternal injury among pregnant drivers in crashes. Additional studies are needed to examine the effectiveness of belt use and other safety devices in reducing the rate of adverse pregnancy outcomes.

APPENDIX A - Results from the DAG analysis

Table A.1. Variable relations for the directed acyclic graph (DAG) to identify potential confounders of the association between crashes and adverse maternal and fetal outcomes

Variables	Direct descendants of the variables
Airbag deployment	Injury, placental abruption, PROM, preterm birth, stillbirth
Alcohol use at the time of the crash	Injury, MVC, vehicle speed
Alcohol use during pregnancy	Alcohol use at the time of the crash, placental abruption, *hypertensive disorders*
Ambient light	MVC, vehicle speed
Belt use	Injury, placental abruption, PROM, preterm birth, stillbirth
Congenital anomalies	Preterm birth, stillbirth
Crash locality	MVC, vehicle speed
Driving	MVC
Education	Alcohol use during pregnancy, maternal age, tobacco use, parity, PROM, prenatal care, preterm birth, stillbirth, placental abruption
Energy transfer (i.e., crash severity)	Airbag deployment, injury
Gestational age	Belt use, MVC, driving, injury, preterm birth, stillbirth
Hypertensive disorders	Preterm birth, stillbirth, placental abruption, PROM
Injury	Preterm birth, stillbirth, placental abruption, PROM
Intrauterine infection	Preterm birth, stillbirth, placental abruption
Marital status	Preterm birth, stillbirth, PROM, prenatal care
Maternal age	Alcohol use at the time of the crash, alcohol use during pregnancy, belt use, *hypertensive disorders,* MVC, number of occupants, parity, preterm birth, stillbirth, placental abruption, PROM, prenatal care, tobacco use, *driving*, vehicle speed
Motor vehicle crash (MVC)	Energy transfer, preterm birth, stillbirth, placental abruption, PROM, *uterine rupture*
Number of occupants	MVC
Parity	Placental abruption, MVC
Placental abruption	Preterm birth, stillbirth
Premature rupture of the membranes (PROM)	Preterm birth, stillbirth, placental abruption, *intrauterine infection*
Prenatal care	Alcohol use during pregnancy, belt use, MVC, parity, preterm birth, stillbirth, PROM, tobacco use
Prior C-section	Placental abruption
Race/ethnicity	Alcohol use during pregnancy, maternal age, parity, prenatal care, preterm birth, stillbirth, placental abruption, PROM, tobacco use, unknown social/behavioral factors
Tobacco use	*Hypertensive disorders,* MVC, preterm birth, stillbirth, placental abruption, PROM
Unknown social/behavioral factors	Alcohol use during pregnancy, belt use, *driving*, maternal age, marital status, education, parity, prenatal care, preterm birth, stillbirth, tobacco use
Unknown causes of stillbirth	*Prior stillbirth*, stillbirth
Unknown causes of preterm birth	Prior preterm birth, preterm birth
Unknown causes of	*Prior placental abruption*, placental abruption

placental abruption	
Unknown causes of PROM	*Prior PROM*, PROM
Other infections	Preterm birth, stillbirth, placental abruption, PROM
Unknown crash characteristics	Injury, MVC
Unknown crash characteristics	Injury
Unknown causes of preterm birth and stillbirth	Preterm birth, stillbirth
Unknown causes of preterm birth and PROM	Preterm birth, PROM
Unknown causes of placental abruption and PROM	Placental abruption, PROM
Unknown causes of adverse pregnancy outcomes	Preterm birth, stillbirth, placental abruption, PROM
Uterine rupture	Preterm birth, stillbirth
Vehicle speed	Airbag deployment, energy transfer, MVC, injury
Vehicle type	Vehicle speed, MVC
Weather	Ambient light, MVC, road surface, vehicle speed

Note: Unmeasured variables shown in italics

Table A.2. Minimally sufficient adjustment sets of covariates identified from the DAG analysis for the association between maternal characteristics and the risk of being a pregnant driver in a crash

Potential Risk Factors	Minimally Sufficient Adjustment Sets[a]
Alcohol use during pregnancy	1. Maternal age, parity, prenatal care, tobacco use, unknown social/behavioral factors 2. Maternal age, parity, prenatal care, tobacco use, driving 3. Maternal age, prenatal care, race/ethnicity, unknown social/behavioral factors, education
Education	1. Unknown social/behavioral factors
Marital status	1. Unknown social/behavioral factors
Maternal age	1. Race/ethnicity, unknown social/behavioral factors, education
Parity	1. Maternal age, prenatal care, race/ethnicity, unknown social/behavioral factors, education 2. Maternal age, prenatal care, tobacco use, unknown social/behavioral factors, alcohol use during pregnancy 3. Maternal age, prenatal care, tobacco use, alcohol use during pregnancy, driving
Prenatal care	1. Maternal age, race/ethnicity, unknown social/behavioral factors, education
Race/ethnicity	None
Tobacco use	1. Maternal age, parity, prenatal care, unknown social/behavioral factors, alcohol use during pregnancy 2. Maternal age, parity, prenatal care, alcohol use during pregnancy, race/ethnicity, driving 3. Maternal age, prenatal care, race/ethnicity, unknown social/behavioral factors, education

[a]DAG analysis conditioned on gestational age

Table A.3. Minimally sufficient adjustment sets of covariates identified from the DAG analysis for the association between driver and crash characteristics and the risk of injury

Potential Risk Factors	Minimally Sufficient Adjustment Sets[a]
Airbag deployment	Energy transfer, vehicle speed
Alcohol use at the time of the crash	1. Gestational age, maternal age, parity, prenatal care, tobacco use, alcohol use during pregnancy, belt use 2. Gestational age, maternal age, prenatal care, unknown social/behavioral factors, alcohol use during pregnancy, unknown crash characteristics, vehicle speed 3. Gestational age, alcohol use during pregnancy, unknown crash characteristics, vehicle speed, belt use 4. Maternal age, parity, prenatal care, tobacco use, unknown social/behavioral factors, alcohol use during pregnancy 5. Maternal age, prenatal care, race/ethnicity, unknown social/behavioral factors, education
Ambient light	1. Gestational age, maternal age, parity, prenatal care, tobacco use, alcohol use during pregnancy, unknown crash characteristics, vehicle speed 2. Gestational age, maternal age, prenatal care, unknown social/behavioral factors, alcohol use during pregnancy, unknown crash characteristics, vehicle speed 3. Gestational age, alcohol use during pregnancy, unknown crash characteristics, vehicle speed, belt use
Belt use	1. Gestational age, maternal age, parity, prenatal care, tobacco use, alcohol use during pregnancy 2. Gestational age, maternal age, prenatal care, unknown social/behavioral factors 3. Gestational age, alcohol use during pregnancy, unknown crash characteristics, vehicle speed
Crash locality	1. Gestational age, maternal age, parity, prenatal care, tobacco use, alcohol use during pregnancy, unknown crash characteristics, vehicle speed 2. Gestational age, maternal age, prenatal care, unknown social/behavioral factors, alcohol use during pregnancy, unknown crash characteristics, vehicle speed 3. Gestational age, alcohol use during pregnancy, unknown crash characteristics, vehicle speed, belt use
Gestational age	1. Alcohol use during pregnancy, unknown crash characteristics, vehicle speed, belt use
Maternal age	1. Gestational age, alcohol use during pregnancy, unknown crash characteristics, vehicle speed, belt use
Number of occupants	1. Gestational age, maternal age, parity, prenatal care, tobacco use, alcohol use during pregnancy, unknown crash characteristics, vehicle speed 2. Gestational age, maternal age, prenatal care, unknown social/behavioral factors, alcohol use during pregnancy, unknown crash characteristics, vehicle speed 3. Gestational age, alcohol use during pregnancy, unknown crash characteristics, vehicle speed, belt use

Race or ethnicity	1. Gestational age, maternal age, parity, prenatal care, tobacco use, alcohol use during pregnancy, belt use 2. Gestational age, maternal age, prenatal care, unknown social/behavioral factors, alcohol use during pregnancy, unknown crash characteristics, vehicle speed 3. Gestational age, alcohol use during pregnancy, unknown crash characteristics, vehicle speed, belt use 4. Maternal age, parity, prenatal care, tobacco use, unknown social/behavioral factors, alcohol use during pregnancy
Road surface	1. Gestational age, maternal age, parity, prenatal care, tobacco use, alcohol use during pregnancy, unknown crash characteristics, vehicle speed 2. Gestational age, maternal age, prenatal care, unknown social/behavioral factors, alcohol use during pregnancy, unknown crash characteristics, vehicle speed 3. Gestational age, alcohol use during pregnancy, unknown crash characteristics, vehicle speed, belt use
Vehicle damage	1. Airbag deployment, vehicle speed
Vehicle speed	1. Airbag deployment, gestational age, maternal age, parity, prenatal care, tobacco use, alcohol use during pregnancy, unknown crash characteristics, vehicle damage 2. Airbag deployment, gestational age, maternal age, prenatal care, unknown social/behavioral factors, alcohol use during pregnancy, unknown crash characteristics, vehicle damage 3. Airbag deployment, gestational age, alcohol use during pregnancy, unknown crash characteristics, vehicle damage, belt use
Vehicle type	1. Gestational age, maternal age, parity, prenatal care, tobacco use, alcohol use during pregnancy, unknown crash characteristics, vehicle speed 2. Gestational age, maternal age, prenatal care, unknown social/behavioral factors, alcohol use during pregnancy, unknown crash characteristics, vehicle speed 3. Gestational age, alcohol use during pregnancy, unknown crash characteristics, vehicle speed, belt use
Weather	1. Gestational age, maternal age, parity, prenatal care, tobacco use, alcohol use during pregnancy, unknown crash characteristics, vehicle speed 2. Gestational age, maternal age, prenatal care, unknown social/behavioral factors, alcohol use during pregnancy, unknown crash characteristics, vehicle speed 3. Gestational age, alcohol use during pregnancy, unknown crash characteristics, vehicle speed, belt use

[a]DAG analysis conditioned on driving and being a driver in a motor vehicle crash

Table A.4. Minimally sufficient adjustment sets of covariates identified from the DAG analysis for the association between crashes and the rate of adverse pregnancy outcomes

	Minimally Sufficient Adjustment Sets
Exposure Motor vehicle crash	**Outcome: Preterm birth rate (unconditional)** 1. Gestational age, maternal age, parity, prenatal care, tobacco use, unknown social/behavioral factors, alcohol (pregnancy), unknown crash characteristics, *vehicle speed* 2. Gestational age, maternal age, parity, prenatal care, tobacco use, alcohol (pregnancy), unknown crash characteristics, *vehicle speed*
Exposure Motor vehicle crash	**Outcome: Stillbirth rate (unconditional)** 1. Gestational age, maternal age, parity, prenatal care, tobacco use, unknown social/behavioral factors, alcohol (pregnancy), unknown crash characteristics, *vehicle speed* 2. Gestational age, maternal age, parity, prenatal care, tobacco use, alcohol (pregnancy), unknown crash characteristics, *vehicle speed*
Exposure Motor vehicle crash	**Outcome: Placental abruption rate (unconditional)** 1. Gestational age, maternal age, marital status, parity, prenatal care, *alcohol (crash)*, race/ethnicity, tobacco use, alcohol (pregnancy), unknown crash characteristics, *vehicle speed, belt use,* education 2. Gestational age, maternal age, parity, prenatal care, tobacco use, unknown social/behavioral factors, alcohol (pregnancy), unknown crash characteristics, *vehicle speed* 3. Gestational age, maternal age, parity, prenatal care, tobacco use, alcohol (pregnancy), unknown crash characteristics, *vehicle speed*
Exposure Motor vehicle crash	**Outcome: Premature rupture of the membranes (PROM) rate (unconditional)** 1. Gestational age, *hypertensive disorders*, maternal age, marital status, prenatal care, race/ethnicity, tobacco use, alcohol (pregnancy), unknown crash characteristics, *vehicle speed, belt use,* education 2. Gestational age, maternal age, marital status, prenatal care, *alcohol (crash)*, race/ethnicity, tobacco use, alcohol (pregnancy), unknown crash characteristics, *vehicle speed, belt use,* education 3. Gestational age, maternal age, parity, prenatal care, tobacco use, unknown social/behavioral factors, alcohol (pregnancy), unknown crash characteristics, *vehicle speed* 4. Gestational age, maternal age, parity, prenatal care, tobacco use, alcohol (pregnancy), unknown crash characteristics, *vehicle speed* 5. Gestational age, maternal age, prenatal care, race/ethnicity, tobacco use, unknown social/behavioral factors, alcohol (pregnancy), unknown crash characteristics, *vehicle speed,* education

Note: Unmeasured variables shown in italics

APPENDIX B - Results from the GEE analysis (Specific Aim 2)

Table B.1. Binomial regression analysis to estimate the risk of injury among pregnant drivers in crashes after the 20th week of pregnancy in North Carolina, by inclusion of GEEs, (N=11,052), 2001-2008

	Without GEE			With GEE		
	RD[a]	NNT	95% CI	RD[a]	NNT	95% CI
Driver characteristics						
Maternal age, years						
16-17	4.1	(24)	-3.2, 11.5	4.1	(24)	-3.2, 11.4
18-24	6.7	(15)	4.7, 8.7	6.7	(15)	4.7, 8.7
25-34	0		Reference	0		Reference
35+	-2.5	(-39)	-5.6, 0.5	-2.5	(-39)	-5.6, 0.5
Race & Hispanic ethnicity						
White	0		Reference	0		Reference
Black	9.0	(11)	6.9, 11.1	9.0	(11)	6.8, 11.1
Hispanic	0.6	(178)	-2.9, 4.0	0.6	(178)	-2.9, 4.0
Other	5.7	(18)	0.8, 10.5	5.7	(18)	0.8, 10.5
Gestational age at time of crash						
20-27	0		Reference	0		Reference
28-32	0.9	(113)	-1.5, 3.2	0.9	(113)	-1.5, 3.3
33-36	0.8	(120)	-1.9, 3.5	0.8	(120)	-1.8, 3.5
37+	1.1	(94)	-2.5, 4.6	1.1	(94)	-2.4, 4.5
Suspected alcohol use at the time of crash						
Yes	6.9	(15)	-7.3, 21.0	6.9	(15)	-8.0, 21.0
No	0		Reference	0		Reference
Seat belt use						
None	20.7	(5)	13.1, 28.2	20.7	(5)	13.2, 28.1
Belt	0		Reference	0		Reference
Vehicle characteristics						
Airbag deployment						
No airbag	0		Reference	0		Reference
Not deployed	-8.3	(-12)	-10.9, -5.7	-8.3	(-12)	-10.8, -5.7
Deployed	21.1	(4.7)	17.4, 24.8	21.1	(4.7)	17.5, 24.7
Speed at impact						
<25 mph	0		Reference	0		Reference
25-45 mph	2.8	(35)	0.7, 4.9	2.8	(35)	0.8, 4.9
>45 mph	3.1	(33)	-0.7, 6.9	3.1	(33)	-1.0, 7.1
Vehicle damage severity						
Damage rating < 3	0		Reference	0		Reference

Damage rating ≥ 3	17.9	(5.6)	15.7, 20.2	17.9	(5.6)	15.7, 20.2
Vehicle type						
Passenger car	6.9	(15)	-3.8, 17.6	6.9	(15)	-3.4, 17.1
Other	0		Reference	0		Reference
Number of occupants						
1 (driver only)	0		Reference	0		Reference
2	1.8	(56)	-0.6, 4.2	1.8	(56)	-0.6, 4.2
3+	1.0	(97)	-1.7, 3.8	1.0	(97)	-1.8, 3.8
Environmental characteristics						
Ambient light						
Daylight	0		Reference	0		Reference
Dark	2.2	(45)	-0.3, 4.8	2.2	(45)	-0.3, 4.8
Crash locality						
Rural	0.1	(2091)	-3.3, 3.4	0.1	(2091)	-3.3, 3.4
Mixed	0		Reference	0		Reference
Urban	-2.3	(-44)	-5.0, 0.4	-2.3	(-44)	-5.0, 0.4
Road surface						
Dry	0		Reference	0		Reference
Wet	1.9	(53)	-0.7, 4.5	1.9	(53)	-0.7, 4.5
Snow/Ice	-5.0	(-20)	-13.2, 3.3	-5.0	(-20)	-13.4, 3.5
Other	10.7	(9.4)	-15.3, 36.6	10.7	(9.4)	-18.9, 40.2
Weather condition						
Clear	0		Reference	0		Reference
Cloudy	-0.04	(-2402)	-2.5, 2.4	-0.04	(-2402)	-2.5, 2.4
Rain or Snow	1.8	(55)	-1.5, 5.2	1.8	(55)	-1.5, 5.2
Other	-2.6	(-39)	-34.5, 29.4	-2.6	(-39)	-36.8, 31.7

Abbreviations: GEE, Generalized Estimating Equations; RD, adjusted risk difference; CI, confidence interval
[a]Adjustment sets are the same as those provided in Tables 5.2-5.5.

APPENDIX C - Results from the binomial regression analysis (Specific Aim 3)

Table C.1. Unadjusted risk and adjusted risk ratio estimates for the association between crashes and adverse pregnancy outcomes in North Carolina, by risk period, (N=878,546), 2001-2008

	Risk period starts at 20 weeks			Risk period starts at 24 weeks			Risk period starts at 28 weeks			Risk period starts at 32 weeks		
	Risk[a]	Risk ratio[b]	95% CI	Risk[a]	Risk ratio[b]	95% CI	Risk[a]	Risk ratio[b]	95% CI	Risk[a]	Risk ratio[b]	95% CI
Preterm birth												
No. of crashes												
0	114.3	1.00	Reference	112.5	1.00	Reference	108.6	1.00	Reference	100.0	1.00	Reference
1	122.3	1.06	1.02, 1.11	120.1	1.06	1.02, 1.11	116.0	1.06	1.02, 1.11	105.2	1.05	1.01, 1.09
2+	149.4	1.29	0.97, 1.73	153.4	1.32	1.03, 1.69	137.7	1.24	0.98, 1.56	120.6	1.19	0.95, 1.50
Stillbirth												
No. of crashes												
0	6.2	1.00	Reference	4.3	1.00	Reference	3.3	1.00	Reference	2.5	1.00	Reference
1	5.9	0.98	0.78, 1.22	4.4	1.04	0.82, 1.32	3.0	0.97	0.74, 1.26	2.0	0.80	0.58, 1.10
2+	26.8	4.71	2.27, 9.79	19.9	4.97	2.39, 10.35	13.5	4.35	1.97, 9.64	7.4	3.15	1.19, 8.36
Placental abruption												
No. of crashes												
0	6.7	1.00	Reference	6.4	1.00	Reference	5.9	1.00	Reference	5.1	1.00	Reference
1	7.5	1.09	0.90, 1.32	7.5	1.14	0.95, 1.36	6.9	1.14	0.95, 1.35	6.1	1.14	0.96, 1.37
2+	11.5	1.65	0.54, 5.09	8.5	1.27	0.41, 3.92	6.8	1.09	0.35, 3.37	9.3	1.74	0.73, 4.17
Premature rupture of the membranes												
No. of crashes												
0	22.4	1.00	Reference	21.7	1.00	Reference	20.8	1.00	Reference	19.6	1.00	Reference
1	25.8	1.14	1.03, 1.26	24.7	1.14	1.04, 1.26	24.0	1.16	1.06, 1.28	22.6	1.17	1.06, 1.28
2+	49.8	2.20	1.29, 3.73	42.6	2.02	1.24, 3.32	33.9	1.66	1.01, 2.73	31.5	1.66	1.04, 2.65

[a]Unadjusted risks per 1,000 pregnant women

[b]Adjusted for gestational age, maternal age, parity, prenatal care, tobacco use during pregnancy, alcohol use during pregnancy

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