



Annu. Rev. Public Health 2006. 27:125–52
doi: 10.1146/annurev.publhealth.27.021405.102225
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SPEED, ROAD INJURY, AND PUBLIC HEALTH

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Key Words speed limits, travel speed, speed cameras, road injury

■ **Abstract** We review milestones in the history of increases in speed limits and travel speeds (“speed creep”) and risks for road deaths and injury. Reduced speed limits, speed-camera networks, and speed calming substantially reduce these tolls in absolute numbers—a trend that is apparent in the United Kingdom, Australia, France, and other countries, but not in the United States, which has raised speed limits and does not have speed-camera networks. Newtonian relationships between the fourth power of small increases or reductions in speed and large increases or reductions in deaths state the case for speed control. Speed adaptation and the interaction between speed and other determinants of injury risks, including congestion and countermeasures, enter into these relationships. Speed-camera networks and speed calming lead to large, sustainable, and highly cost-effective drops in road deaths and injuries and should target entire populations, not merely high-risk subgroups or situations. Yet, there are major barriers to preventive strategies based on the discovery that speed kills. Modal shifts from speed on roads to speed on rail, lower maximum vehicle speeds, and speed-camera networks are required for progress toward Vision Zero—the goal of no road deaths—through Killing Speed. The human cost of the delay in killing speed in the United States may be as high as 20,000 lives lost per year.

Speed Kills, Kill Speed.

—The Slower Speeds Initiative

<http://www.slower-speeds.org.uk/>

*The challenge is for the driving public to see speeding as equally antisocial as
drink driving.*

—Adrian Walsh, Director, RoadSafe

<http://www.roadsafe.com/>

*Thus spake Joshua to the Lord. . .Sun, stand still in Gibeon, .. and Moon in
Ayalon . . . And the sun stood still and the moon stayed . . . And there was no day
like it before or after that the Lord listened to a voice of a man.*

—Joshua X:12–14

INTRODUCTION

Since the first motor car death in 1896, the worldwide cumulative road death toll has reached some 30 million persons and now is ~ 1.2 million deaths per year. The annual road death toll is 134,000 in the Americas, 127,000 in Europe, 190,000 in Africa, 132,000 in the Eastern Mediterranean, and 600,000 in Southeast Asia and the Western Pacific. An additional 50 million people are reported as injured in road collisions each year, many with severe, permanent disabling injuries of the brain and spinal cord. Road traffic injuries cost $\sim \$518$ billion per year, of which $\$100$ billion is borne by poor nations. Because most of the victims of road collisions are young, person years lost (PYL) per death are high. By 2020, road deaths will rise by 65% and will be the third ranking cause of death (72). We ask, would a new technology for moving persons from point A to point B be tolerated if the human toll was 1.2 million deaths per year?

Transportation's progress through the centuries is defined by time saved, which means faster speeds, a uniquely human achievement. But an elementary consideration of the biomechanics of injury underscores the dominant role of speed in road death and injury. The ABCs of injury epidemiology are determined by exponential Newtonian relationships between speed of impact, kinetic energy, and injury severity. The ABCs of the behavioral psychology of speed derive from the fact that fear of speed, unlike fear of heights, is not inherited.

The move toward higher speeds and increased individual mobility began in the United States with the first Model T Fords in 1908, which had cruising speeds of ~ 35 –40 mph, and in pre-World War II Europe with Mussolini's construction of the Autostrada in Italy and Hitler's construction of the Autobahn in Germany (23, 32). Speed creep remains a poorly managed risk to this day. Waller (111) has used the Haddon Grid to review the role of precrash-, crash-, and postcrash-phase countermeasures in the United States, including the benefits from federal motor vehicle safety standards (FMVSS), seat belt laws, measures against drunk driving, and speed limits in reducing risks for road injuries and deaths. We focus specifically on speed and the effects of kinetic energy of impacts, the pathogenic event in road injury, and the results of the latest strategies to kill speed. The case for action for this review is the failure of the United States to reduce its road death tolls in absolute numbers in the past decade and the stunning successes elsewhere from killing speed (29, 79).

We reject the ethically problematic paradigm in which loss of human life from increased speeds of travel is an accepted price worth paying for esoterically defined gains in time savings.

SPEED RISKS AND SPEED CONTROL: SIX MAJOR MILESTONES

The reader should refer to Table 1 for the following sections.

TABLE 1 The six major milestones

1. Discovery that kinetic energy is the pathogen in road injury.
2. Drop in road deaths following lower speed limits of 1973 energy crisis.
3. Nilsson's fourth power model $\Delta\text{Deaths} = \Delta\text{Velocity}^4$ and similar models for pedestrians.
4. Return to higher speed limits in the United States and on major sections of Germany's Autobahn.
5. Drops in road deaths after introduction of speed cameras and speed calming.
6. Sweden's adoption of the Vision Zero model.

First Milestone: Kinetic Energy is the Pathogen

The first milestone was the discovery that the basic laws of physics operate in human injury, which emerged from pioneering research by DeHaven and Stapp during the 1940s and 1950s. DeHaven first documented the effects of free falls on hard, soft and hollow tissues of human cadavers (17). Stapp's famous experiment in 1954, in which he emerged unscathed from a rocket sled into which he was restrained and which decelerated from a velocity of 632 mph (1011 kph) in 1.4 seconds, proved that kinetic energy of impacts, and not acceleration or deceleration, was the critical issue in injury mechanics (22).

Stapp's and DeHaven's experiments were the forerunner of the U.S. federal motor vehicle safety standards (FMVSS), which introduced three generations of crash phase vehicular and environmental countermeasures to diminish, dissipate, or divert kinetic energy impacts delivered to the human body. Because these countermeasures made crash impacts safer, maximum design speeds of cars began creeping upward. National Highway Traffic Safety Administration (NHTSA) has speculated that had seat belts and other countermeasures never been introduced, there might have been greater emphasis on the importance of speed control (49). Today half of the speedometer on most vehicles is wasted on indicating speeds that should never be driven. Yet, the limits of the modern vehicle to protect against fatal crash injury are still mediocre: below 40 kilometers per hour (kph) for a pedestrian, 50 kph for occupants impacted from the side and for impacts with rigid roadside objects, and 70 kph for passengers in frontal impacts (45).

Second Milestone: Road Deaths Drop Following Lower Speed Limits of 1973 Energy Crisis

The second major milestone was the sudden and unanticipated fall in total death tolls with lower speed limits during oil embargos following the 1973 war between Israel and the Arab states. The U.S. Congress, in an effort to reduce fuel consumption, imposed a nationwide 55-miles per hour (mph) speed limit in 1974, and some European countries followed suit. Table 2 summarizes major studies that documented the reductions in deaths following reduced speed limits in the 1970s. The results from all these studies were strikingly consistent even though all but

TABLE 2 Major studies on lowered speed limits, 1973 forward

Citation	Country, year of speed limit change, change in speed limit	Method	Results	Comments
United States Partyka 1984 (71)	United States, 1974, 65 to 55 mph	Linear regression model	Significant decrease in fatalities system-wide	Controls only for employment and population size
NRC 1984 (63a)	United States, 1974, 65 to 55 mph	Before-after comparison	3000 fewer fatalities and a reduction of 3500 serious injuries after speed limit reduction	
Europe, Australia Engel & Thomsen 1992 (24)	Denmark, 1977, speed limits reduced by 15 and 30 kph on 223-km residential roads	Crude before-after comparisons and 44 experimental streets with detailed analysis using before-after traffic data	Drop of 77 accidents and 88 casualties during 3 years following reduction in speed limit. On experimental roads, severe injuries dropped by 78%	Data suggest importance of decreased speed of crash impact in reducing severe injuries
Walz et al. 1983 (112)	Switzerland, 1983, 60 to 50 kph	Before-after comparison of pedestrian fatalities	25% drop in pedestrian fatalities in the year following the reduction in speed limit	
Nilsson 1990 (65)	Sweden, 1989, 110 to 90 kph		Fatal crashes dropped by 21%; 14 kph drop in travel speeds	
Sliegeris 1992 (97)	Australia, 1989, 110 to 100 kph	Before-after comparisons of (a) after raise in speed limit, (b) after lowered again	After speed limits were lowered again the injury crash rates dropped 19.3%	Based only on crash data, not casualties alone or CFR
Johansson 1996 (44)	Sweden, 1989, 110-to 90 kph	Time series, used several models	Statistically insignificant decrease in both crashes with fatalities and severe injuries	Based on crash data, not actual number of casualties

one of these studies used crude before-after comparisons and databases on deaths and injuries in the era before standardized injury severity scores became available. In the United States, the 55-mph limit resulted in a reduction in highway fatalities of more than 9000 in the first year and between 3000 and 5000 fatalities annually thereafter. By 1984, there continued to be between 2000 and 4000 fewer fatalities and between 2500 and 4500 fewer serious, severe, and critical injuries compared with preembargo tolls. Although some of the drop was attributed to a 3% drop in motor vehicle travel, lower speeds were credited with most of the decline (102).

Third Milestone: Return to Higher Speed Limits in the United States and Europe

The third milestone was the rejection of the lessons of the 55-mph limit and the return to higher speed limits in the United States and Europe. In the United States, there was a gradually upward trend in speeds, especially in interurban U.S. highways, and higher death tolls starting in the 1980s. Germany's Autobahn became noteworthy for major stretches without speed limits for private motor vehicles, excluding trucks, but congestion probably mitigated some of the effects of speed (30). There has been a substantial literature on the effects of two cycles of raised speed limits, but not all studies provided data on actual rises in speeds (Table 3). Most of the studies used time-series models to track trends in deaths and injuries separately. NHTSA and others found that following the 1987 raise of speed limits on U.S. rural roads, there was a 2–3 mph (or 4.8%) increase in mean speeds and a 21% increase in fatalities (7). Following a second round of raised speed limits after 1995, average interstate speeds and deaths increased in many U.S. states by some 4% and 17%, respectively, in keeping with predicted fourth-power relationships (31) (see below). By 2003, most U.S. states had raised speed limits to 70 mph or higher on some portion of their roadway systems, a measure that resulted in between 35% and 38% more deaths in these states (42).

An Israeli study on the effect of raised speed limits tracked trends in case fatality rate (CFR), a parameter that is independent of vehicle kilometers travel (vkmt) and is a direct measure of the effects of speed of impact, seat belt use, and trauma care. Following an increase in speed limit from 90 to 100 kph, interurban road speeds increased by 4.5%, deaths increased by 15%, and CFR rose by 38%. On urban roads, deaths rose by 13% and CFR rose by 24%. This study showed that rises in CFR accounted for all the rises in deaths, that systemwide rises in deaths in absolute numbers occurred despite falls in deaths/billion vehicle kilometers travel (bvmt) from congestion and countermeasures, and that raised speed limits on high-speed roads would not be protective systemwide (81).

Some studies showed that the effects of increased speed limits are not limited to high-speed roads. Speed adaptation and spillover effects occur when drivers coming off high-speed roads continue to drive faster than those already on the same road (10, 11, 94) and may account for more deaths than on the safer roads with higher design speeds. Therefore, studies in which time trends on lower speed “spillover”

TABLE 3 Major studies on increased speed limits

Citation	Country, year of speed limit change, change in speed limit	Methods	Results	Comments
Solomon et al. 1974 (99)	United States, 1964	Analysis of 10,000 crashes. Relationship between travel speed and injury severity	Crash severity increased exponentially with an excess of 60 mph, and risk of fatal injuries increased sharply above 70 mph	First study involving individual data. Findings on increased risk with extremely low speeds later refuted
Rock 1995 (90)	Illinois, United States, 1987, 55 to 65 mph	Time series, ARIMA, 1982–1991	Results for 65 mph and 55 mph roads respectively: Accidents increased 33% and 6%; injuries increased 19% and 6%. Deaths increased 40% and 25%	Findings indicate spillover effect
Lave & Elias 1994 (52)	United States, multiple states, 1987, 55 to 65 mph	Before-after comparison and regression models	Statewide fatality rates/VMT* fell 3.4% to 5.1%	Based on rates with a denominator of VMT
Wagenaar et al. 1990 (110)	Michigan, United States, 1987, 55 to 65 mph	Time series, ARIMA, 1978–1988	After 1987: Increases in fatalities 19.2%, serious injuries 39.8%, and moderate injuries 25.4%	Fatalities increased on 55 mph limited-access freeways, indicating spillover effect. Analysis limited to very brief posteffect period
Garber & Grahman 1990 (35)	40 U.S. states, 1987, 55 to 65 mph	Time series, regression analysis, 1976–1988, FARS data	Fatalities increased 15% on rural interstate roads (65 mph), 5% on rural noninterstate roads (55 mph)	Analysis limited to very brief posteffect period

Gallaher et al. 1989 (34)	New Mexico, United States, 1987, 55 to 65 mph	O/E rates based on 5-year baseline compared with 1 year after speed limit raise	Fatalities/VMT increased 2.9 d/b VMT compared with an expected rate of 1.5d/b VMT	Analysis based on fatality rates (VMT)
Baum et al. 1989 (7)	40 states in United States, 1987, 55 to 65 mph	Before-after comparison 1982–1989	More fatalities on rural roads: interstates (65 mph): 19%; non-interstate roads (55 mph): 4%	Indicates spillover effect
Chang et al. 1993 (13)	32 states in United States, 1987, 55 to 65 mph	Time series, ARIMA, 1975–1999 only in state that raised speed	Fatalities: significant increase on rural interstate roads	
NHTSA 1989 (63a)	United States, multiple states, 1987, 55 to 65 mph	Multiple regression analysis	Fatalities 21% higher than expected on rural interstate roads with 65 mph	FARS database
Streff & Schultz 1991 (100)	Michigan, United States, 1987, 55 to 65 mph	Time series, ARIMA, 1978 to 1989	On 65-mph interstates, statistically significant increase of crashes with fatalities (28.4%), serious injuries (38.2%), and moderate injuries (24.0%). No significant changes were observed on 55-mph roads	Analysis based on crashes not casualties
Sliogeris 1992 (97)	Australia, 1987, 100 to 110 kph	Before-after comparisons of two periods (a) after raise in speed limit, (b) after lowered again	Injury crash rates increased 24.6%	Based only on crash data, not casualties alone or CFR

(Continued)

TABLE 3 (Continued)

Citation	Country, year of speed limit change, change in speed limit	Methods	Results	Comments
Parker 1997 (70)	United States, many states 1985–1992: reductions before 1987: 5–10–15–20 mph; canceled in 1987	Analysis based on changes on small segments of roads usually less than 2 miles in length	No significant decrease in crashes on roads with lowered speed limits	Based on crash data only, without casualties
NHTSA 1998 (61)	United States, 1995/1996, 55 to 65/75mph	Linear regression model and crude before-after comparison in 11 states that raised limits	Significant increases in fatalities and injuries. Estimated 356 excess fatalities in the first year after the change in speed limits	Post-change period analyzes only one year after. CFR is not included in the analysis. Data missing on many socioeconomic and VMT variables
Patterson et al. 2002 (71a)	United States, 1995/1996, 65 to 70–75 mph	Poisson regression model. Compared states with rural interstate limits at 65 mph to states that raised it further to 70–75 mph	70 mph roads: fatalities rose 35% (CI 95% = 6%, 72%); 75 mph roads: fatalities rose 38% (CI 95% = 8%, 78%).	Only covariate was VMT

Farmer et al. 1999 (31)	24 U.S. states, 1995–1996, 55 to 65–75 mph	Time series cross section regression	Speeds increased 4%, fatalities increased 14.8% (CI95% = 7.1%, 23.1%), fatality rates (VMT) increased 17%	Based on FARS, fatality data only. Controlled for economic trends. No evidence of spillover—follow-up for only 1.5 years
Ossiander & Cummings 2002 (68)	Washington, United States, 1987, 55 to 65 mph	Poisson regression, 1974–1994	Fatal crashes more than doubled after 1987 (RR = 2.1; CI 95% = 1.6–2.7)	Based on crashes and VMT as denominator; no support for speed variance theory
Richter et al. 2004 (81)	Israel, 1992–1998, 90 to 100 kph in 1993	Before-after comparison of both urban and interurban roads; 3 years before and 5 years after change analyzed	On interurban roads speeds increased 4.5%; deaths increased 15% and CFR rose 38%. On urban roads, deaths rose 13% and CFR rose 24%. Increases in all driver-crash type subgroups	Analysis includes case-fatality rates, speed-death relationships. Strong evidence of spillover. CFR trends indicate effects concealed by D/vkmt trends
Bartle et al. 2003 (6)	Alabama, United States, 1996, 65 to 70 mph	Time series, 1984–1999	Significant increase in fatalities on rural interstate roads	Increase only in first and third year after raise, not second year
Vernon et al. 2004 (107)	Utah, United States, 1995–1996, 55 to 65–75 mph	Time series, ARIMA, 1992–1999	Significant increase in total crash rates on urban (60–65 mph) interstate segments, not on rural interstate	Based on crash data not casualties. Denominator is VMT

Abbreviations: VMT, vehicle miles traveled; O/E, observed/expected ratio; CFR, case fatality rate.

roads serve as “controls” for trends on high-speed roads may erroneously produce false negative results on the effects of speed (81). Various studies, including one using modern measuring equipment (51), have undermined the claim (99) that speed variance, i.e., driving slower than average speeds, increases crash risk.

Fourth Milestone: Nilsson’s Fourth Power Model $\Delta D = \Delta V^4$

The fourth milestone was the discovery by Nilsson and others on the basis of empirical findings from studies, including those reported in Tables 2 and 3, showing that increases and decreases in travel speeds led to increases and decreases in crashes, injuries, and deaths to the first, second, and fourth power, respectively (64) (Figure 1). These empirical relationships behaved algebraically, in keeping with models derived from Newtonian physics (27), and were not captured by statistical models that separately tracked trends in speed, injuries, and deaths.

Following Nilsson, Joksch showed that in individual crashes, crash fatality in occupants increased as a function of an approximate fourth power of the rise in impact velocity (46) (Figure 2). Since then, others have found approximately the same relationships (27, 30). The fact that the injury severity score, which predicts mortality, is calculated from the sum of the squares of the abbreviated injury score for individual parts of the body (36) captures the second-power relationship between injury and death risk. Using Nilsson’s models, a 3.5%–5% reduction in average travel speeds would be expected to achieve a 15%–21% reduction in deaths,

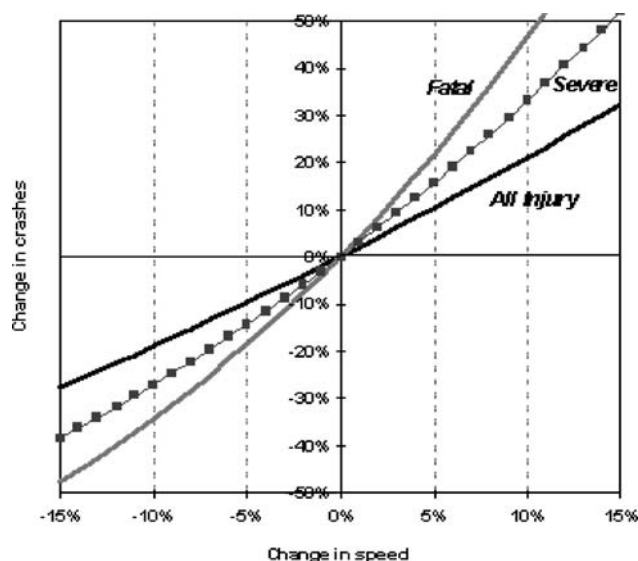


Figure 1 Effects of changes in speed on injury and fatal crashes: empirical relationships (from 64).

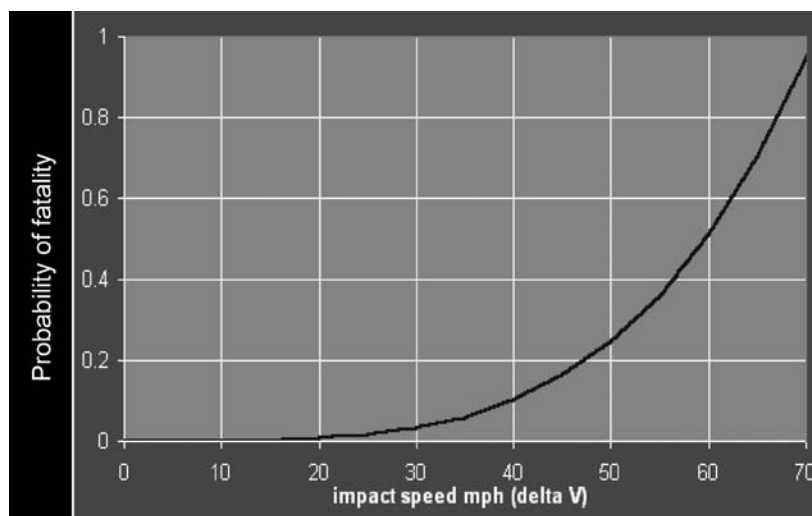


Figure 2 Effect of change in speed at impact on fatality risk (based on 46).

which approximates one estimate of the total reduction achieved by combined effect of all U.S. federal motor vehicle safety standards—itsself a nontrivial benefit (30). The Nilsson fourth-power relationship holds approximately for both belted and unbelted occupants, but the regression line is shifted to the right for the former and is strikingly robust in virtually all scenarios (28).

The exponential relationship between higher speeds and road deaths holds true for pedestrians on urban roads as well. This group includes large numbers of children, the elderly, and the poor. In pedestrian settings, case fatality rises exponentially with increase in impact speeds exceeding 30 kph (92). This finding is the basis for the advances in pedestrian protection provided by 30-kph speed limits, humps, bumps, roundabouts, and painted zebra-stripes in environments of mixed use, separation of pedestrians and cyclists on roads with speeds above 30 kph, and “soft” bumpers on vehicles (53). See Figure 3.

SPEED AND HIGH-RISK HIGHWAYS Everywhere, crash and death rates per vkmt are much lower on high-speed roads (motorways in the European Union and interstates in the United States), compared with other roads, including urban roads, because of their superior design standards. Furthermore, as speeds increase or decrease, the effect of a given reduction in speed has been found to be greater on lower-speed than on high-speed roads (1), although some U.S. studies (Tables 2 and 3) suggest otherwise. Whatever the case, there should be major benefits in injury reduction from control of what is called inappropriate speed from speed spillover (30).

Although death risks/bvkmt are generally lower on highways with higher design speeds compared with feeder roads, there are wide inter-country variations in risks

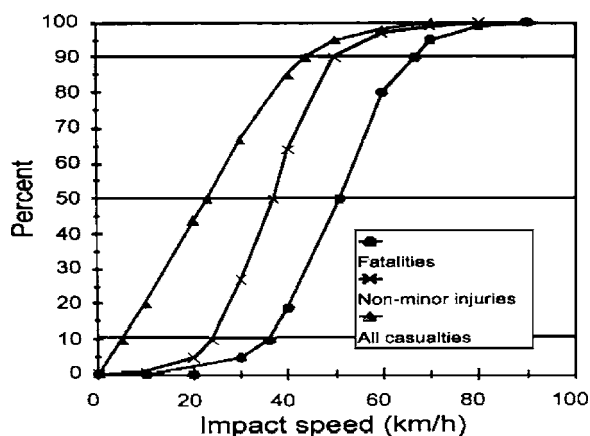


Figure 3 Effect of impact speed on pedestrian injuries and fatalities (55).

on such highways. In 2002, the German rate of 4.1 deaths/bvkmt on motorways was 22% lower than the U.S. rate but was 64% and 95% higher than the Swedish and British rates, respectively (43), and 18% of all crashes in Germany are speed related (12). The risks are much higher in high-speed motorways in countries in Southern Europe and are still far higher in Eastern Europe, Latin America, Asia, India, and Africa.

SUBGROUPS AT SPECIAL RISK Speed and increased speed limits accounts for much of the increased risks for road death and injury in high-risk subgroups, i.e., young drivers, drunk drivers, and drinking drivers, fatigued professional drivers, motorcyclists, and cell-phone users. Whatever the attributed cause or circumstance of crash risk, speed control would reduce the risks in each of these subgroups. In extreme situations, the risks of youth, speed, nighttime, fatigue, alcohol, cell phones, and mass of heavy vehicle interact.

Young drivers. Young male drivers in particular are at special risk for involvement in fatal crashes. Their age-sex increase in risk coincides with that for speed violations per vkmt driving (37), criminal arrests, and high testosterone levels (30).

Drunk and drink driving. The dose-response relationship between alcohol and crash severity suggests that alcohol's main influence is changing driver behavior toward accepting higher risks and choosing higher speeds (30), perhaps because of impaired speed perception (47). Drinking drivers involved in crashes are more likely to be speeding than nondrinking drivers (40, 73). In 2003, 41% of U.S. drivers with a blood alcohol concentration (BAC) of 0.08 g/dl or higher involved in fatal crashes were speeding, compared with 14% of drivers with BAC = 0 involved

in fatal crashes (62). Drivers with illegal BAC of 0.05 were observed in Adelaide, Australia, to drive ~ 3 km/h faster than BAC = 0 drivers and were twice as likely to exceed 65 kph (50). The fact that driving while intoxicated (DWI) increases risk for speeding states the case for screening speeders for problem drinking and alcohol abuse.

Speed and working conditions in professional drivers. Increased speeds combine with fatigue from long work hours, shift work, and incentive premiums in drivers of heavy vehicles, buses, and taxis to increase their risks for involvement in injury-producing crashes. These risks, in the case of trucks and buses, are especially severe because of the destructive power of mass combined with velocity of impacts—even at low speeds (93).

Cell-phone users. Driver simulation studies have shown that cell phones impair drivers' speed-management performance, sometimes resulting in significantly lower speeds (2, 76) or higher average and curve speeds (14). In real-world crashes there are associations between cell-phone use and unsafe speeds (109), and there are increased crash risks from cellular-phone use on high-speed roadways, compared with lower-speed roadways (77).

Motorcyclists. Motorcyclists drive faster both in simulated and real-world settings (39), show a higher disregard for speed limits (56), and are involved in more speed-related crashes than are other drivers. In 2002, 36% of U.S. motorcyclists involved in fatal crashes were speeding, twice the rate for drivers of passenger cars or light trucks. In motorcycle drivers aged 20–29, speeding was implicated in more than 50% of fatal crashes (62). Helmet use has reduced the incidence of only selected brain injury types in motorcyclists since subdural or diffuse brain injuries, which generally occur from high-speed impacts, are mostly unaffected by helmet use (95).

INTERVENTION STUDIES TARGETED AT VERY HIGH SPEEDERS Strong interventions (e.g., license revocation and vehicle impoundment) targeted at drivers involved in fatal crashes, with prior records of speed violations, achieved reductions in subsequent risk of up to 40%, not always of enduring impact (Table 4). The implication of such studies is that major sustained reductions in total death tolls require population-wide strategies for shifting the entire speed distribution curve to the left and not merely targeting high-risk subgroups.

SPEEDING, REACTION TIME, AND HEADWAY INTERVALS There is a substantial literature on speeding, headway intervals, and reaction time, which integrates data from simulation studies and crash investigations on risks for crashes in relation to each of these three parameters (78). In everyday terms, measuring headway in terms of time intervals (e.g. two to three seconds) between passing a specified point is more ergonomically friendly than gauging distances. Instruments that

TABLE 4 Summary of epidemiologic study on the effect of speed violations on individual risk

Citation	Country	Study design	Counter measure	Outcome
Redelmeier & Tibshirani 2003 (77a)	Canada	Case-crossover hazards model	Traffic convictions	35% reduction in fatal crash risk in month following conviction (CI 95%: 20%–45%; $p < 0.001$)
DeYoung 1999 (18)	California, United States	Ecologic ANCOVA	Vehicle impounding	Vehicle impounding associated with a 24.7% reduction in crashes among first-time offenders and 37.6% reduction among repeated offenders
Masten & Peck 2004 (57)	United States	Meta-analysis	License suspended or revoked for DUI convictions	17% decrease in crash rate observed among drivers whose licenses were suspended or revoked. Other forms of intervention showed lower effect on crash rates
Zaidel 2002 (114)	Multiple countries	Meta-analysis	Manual/stationary speed enforcement	2% decrease in all accidents and a 14% decrease in fatalities
DeYoung & Gebers 2004 (19)	California, United States	Ecologic poisson regression	License suspended or revoked	Highest risk of fatal/injury crashes among drivers with suspended/revoked licenses for serious offences (RR = 9.5) and negligent operation (RR = 8.3)*
Rajalin 1994 (75)	Finland	Case-control logistic regression	Traffic convictions	Drivers involved in fatal crashes had more prior traffic convictions than other drivers

*Serious offenders include persons convicted of road rage, reckless driving, or manslaughter. Negligent operation offenses include cumulative traffic violations or crashes (e.g., speeding).

measure both speed and headway intervals (“speed gating”) offer the potential for quantifying “aggressive” or “reckless” driving (82).

Fifth Milestone: Drops in Road Deaths Owing to Introduction of Speed Cameras and Speed Calming

The fifth milestone was the introduction of speed cameras in Victoria (Australia), the United Kingdom, and Norway, accompanied by the pithy slogan, “Speed Kills, Kill Speed.” The potential of speed-camera networks for achieving large

reductions in road death tolls is such that they increase levels of detection to levels that deter, and their revenues more than sustain their operations. Following deployment of massive regionwide speed-camera networks, there were sudden large and sustained drops in road deaths (20, 66, 89). Based on results from simple before-after observations, Australia, the United Kingdom, and Norway expanded their speed-camera networks, and other countries, including Canada, France, Finland, and New Zealand, introduced speed cameras during the 1990s (59). Time trends for road deaths in countries with and without speed-camera networks make the case for large benefits (Figure 4, see color insert). In the United States, where there are no speed cameras on interstates (29, 67), there has been a 5% drop in road deaths since 1990, but there were increases in the mid and late 1990s directly attributable to increased speed limits and travel speeds (85). But in the United Kingdom, where there are 6500 cameras, and Australia, where there are about 54 operational mobile speed cameras deployed at 4500 sites producing 6000 operational hours per month in Victoria and about 100 fixed speed cameras in New South Wales (Ian Johnston, Monash University, Australia, personal communication, May 4, 2005), deaths have dropped by 40% and 45%, respectively (67) (Figure 4). The implication of these trends is that the toll from delay in introducing these systems into the United States is in the range of 13,500–17,200 deaths per year, and even higher, if Victoria, where the reduction has reached 50%, is the model (108). Appendix 1 lists Web sites with information on speed-camera networks.

In the United Kingdom, by 1996, 102 roadside cameras served more than 700 sites. Injury crashes at speed camera sites fell by 28% and 18% at traffic-light sites following installation (38). On ring roads around London controlled by roadside speed cameras, death tolls fell up to 70% (113). Benefits from speed cameras include systemwide crash reduction and crash reduction at individual crash sites. Within the United Kingdom, following introduction of speed cameras at study sites compared with control sites, the odds ratios for slight casualties were 0.92 and were 0.29 for fatal casualties (104). A review, modeled on the Cochrane strategy, of 14 before-after observational studies on the effects of speed cameras from a wide variety of geographic settings reported results ranging between 17%–71% reduction in deaths and 12%–65% reduction in injuries at camera sites, with effects lasting up to 4.6 years after introduction (74). One study on the effects of speed cameras at 101 sites found significant decreases in all types of injury crashes, including those occurring in daytime and nighttime, on roads with speed limits of 30 and 60–70 mph, and for crashes that injured pedestrians, motorcycle users, and car occupants (15). More recent data show that benefits at one site are not offset by more crashes from diversion of traffic to other sites (16). Ben-David et al. (8) carried out a pilot intervention study in two cities in which use of a speed camera led to a leftward shift of the entire speed distribution, resulting in large falls in deaths and injuries among both pedestrians and occupants on roads and intersections.

SPEED CALMING Speed-control policies in the United Kingdom and many European countries have included restricted zones with special speed limits, special

speed limits for trucks, and, in urban areas, road bumps, roundabouts, chicanes, gateways, and other environmental measures. Speed calming from roundabouts has produced reductions in deaths and injuries of 37% and 11%, respectively (pooled estimates) (9).

TARGETING SICK POPULATIONS/SICK SYSTEMS OR SICK INDIVIDUALS/ROADS It is a fundamental principle of epidemiology that small reductions in risk in the entire population save more lives than do big reductions in risk in the small number of high-risk individuals (91). Currently, strategies for positioning speed cameras are based on targeting high-risk spots, as in the United Kingdom, or shifting the speed distribution to the left throughout the road system, as in Victoria. The fact that deaths continue to drop in Australia, and even more so in Victoria, compared with the United Kingdom, provides empirical support for the hypothesis that the second strategy should achieve larger proportional reductions in deaths as compared with the first strategy. If, for example, 10% of the driver population exceeding speed limits is involved in crashes producing 300 (30%) of 1000 deaths, then fourth-power models imply that a 10% reduction in speeds applied to the high-risk group will reduce the death toll from this group by 135 deaths, and a similar proportional reduction in speeds should reduce the death toll among the remaining 900 drivers by 315 deaths.

UNITED STATES AND UNITED KINGDOM: SPEED CREEP VS. KILLING SPEED Currently, higher speed limits, gradually increasing travel speeds (speed creep), and speed spillover from speed adaptation are the most plausible explanations for the fact that deaths are not dropping nationwide in the United States, despite more countermeasures (e.g., increase in seat belt use, more and better trauma care, air bags, drops in DWI) and increased congestion in the Northeastern states (67, 86). In the United States, CFR, which, as already noted, varies with the second power of changes in speed and is independent of exposure, has fallen only trivially, whereas in the United Kingdom it has decreased sharply since 1990. The fact that deaths and CFR began falling right away in the United Kingdom suggested an immediate direct and specific impact from speed cameras. The differing trends in CFR account for the differences in time trends in deaths in the two countries (85) (Figure 5). Furthermore, we suggest that increasing pressures for speed creep are created by more and more urban sprawl, which itself increases risks for road deaths (30a).

COST-EFFECTIVENESS Speed-camera networks have proven to be remarkably cost effective. In a two-year pilot study of cameras in six counties, the cost of camera enforcement was nearly one third that of the total cost of casualties prevented. In the United Kingdom, speed cameras generated an average return of 5 times the investment after 1 year and 25 times the amount after 5 years. In 2003, the benefits from avoided injuries were in excess of £221 million (\$367 million), more than 4 times the £54 million (\$89.9 million) cost of enforcement (33).

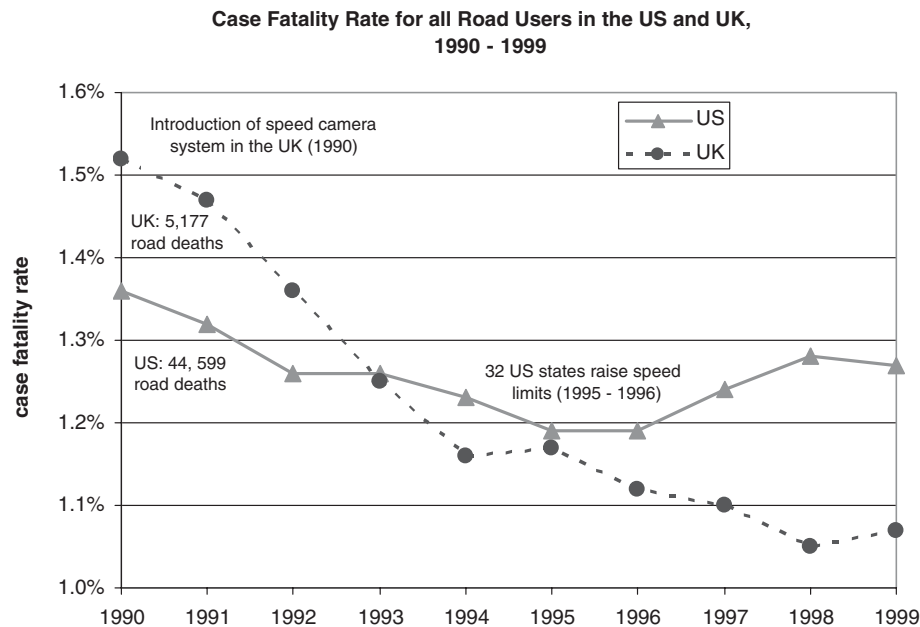


Figure 5 Case fatality rate in the United States and the United Kingdom, 1990–1999.

Sixth Milestone: Sweden Adopts the Vision Zero Model

The sixth milestone was the Swedish Parliament's adoption of the Vision Zero program (VZ) as the ethical norm and ultimate goal of transport policy. VZ aims for zero road fatalities and serious injuries (101). Vision Zero explicitly means that progress in road safety should be measured by drops in the absolute number of deaths as well as deaths/vkmt. The adoption of this term went along with decisions based on comparing deaths/person-kilometers travel or deaths/ton-kilometers travel from alternative modes of transport (Table 5). The fact that death risks from

TABLE 5 Deaths/100 million person-kmt for different modes of transport

Mode of transport	Deaths/100 million person-kmt
Road	0.95
Motorcycle	13.8
Foot	6.4
Cycle	5.4
Car	0.7
Bus	0.07
Rail	0.035

train travel are one twentieth that of car travel (26) states the case for promoting speed on rail as a strategy, which complements killing speed (Table 5). But the vulnerability of pedestrians and cyclists to lower speed impacts persists (48).

EIGHT MAJOR BARRIERS TO KILLING SPEED

Major institutional and political bodies have rejected or resisted the case for speed control. We identified eight barriers to policies that save lives and protect health by reducing speed (see Table 6).

The first barrier to killing speed is the fact that time saved, the product of higher travel speeds, is itself the benefit, in the same way that benefits attributed to pesticides derive specifically from their toxic properties. Increased mobility itself is seen as a good thing, going along with individual freedom, liberty, and the pursuit of happiness.

The second barrier is the fact that speed sells. Speed is marketed not as an economic value but as a thrill with addictive properties (67), lacking the restraint of an inherited fear. The target age-sex group for car sales is young male drivers, the group at greatest risks for speed-associated deaths. Humans are unique in that they are the only animals able to produce speeds greater than their running speed, despite the vulnerability of their bodies to high-speed impacts. We suggest that speed creep and speed adaptation predispose drivers to road rage when high-risk driver subgroups suddenly encounter slowdowns or congestion.

The third barrier is that police investigations and reporting systems mistakenly equate attributed circumstance of crash with cause for injury. Speed of impact, the underlying determinant of injury severity, is usually not the reported cause in most official reporting systems, which are legally oriented in terms of individual blame and liability or circumstance for the “accident” and not risk for the injury. Equating circumstance with cause leads to fundamental distortions in defining priorities for enforcement. For example, in February 2005, the Israeli police announced they would no longer issue tickets for travel speeds less than 25% above the existing speed limit because “speed caused only 6% of all accidents” (E.D. Richter, letter to Israel State Attorney General, Feb. 6 2005).

TABLE 6 Major barriers to accepting the role of speed in road death and injury

1. Time saved from speed is itself the benefit.
2. Speed sells.
3. Reporting systems equate attributed circumstance of crash with cause for injury.
4. Indifference to effects of speed creep.
5. Ideological and institutional barriers.
6. Epidemiological overstatement of the benefits from crash-phase countermeasures.
7. Epidemiological understatement of the risks of speed by “correcting” for exposure.
8. Compartmentalization of traumatic injury and environmental impacts.

The fourth barrier is epidemiologic indifference to speed creep and its effects, especially in North America. The large network of injury prevention centers in the United States has withdrawn from addressing raised speed limits and speed creep. Lower speed limits and use of speed cameras have not appeared on recommendations for preventive strategies in U.S. policy statements and professional reviews (4, 88, 105), as opposed to progress in the United Kingdom (21, 33, 48, 96). The peer-reviewed literature has lagged behind major institutional Web sites in transportation safety in the United Kingdom (Department of Transportation), Australia (Australian Transport Safety Bureau), the European Union (Transport), and the United States (NHTSA) (Appendix 1). The World Health Organization (WHO) injury prevention conferences in 2002 and 2004 contained fewer than 10 abstracts on speed control and speed cameras.

The fifth barrier is that benefits from crash phase countermeasures may have diverted attention away from speed. In the United States, NHTSA calculations that such countermeasures have reduced deaths by up to 42% may be overestimates (30), even though there is already a 17-fold variation in driver death rate between the safest and most dangerous vehicle in which to crash (41). However, the science of countermeasures developed asymmetrically and is directed toward the dissipation, distribution, and management of the impacts of high kinetic energy rather than measures to reduce its creation to begin with, such as a lower maximum built-in vehicular speed.

The sixth barrier is epidemiologic underestimation of the risks from speed creep. Underestimating the dangers of increased speed limits and travel speeds may result from the epidemiologic practice of “correcting for exposure,” as seen in many studies in Table 2. Everywhere the risk for deaths/10,000 vehicles or per vkmt or other indicators of “exposure” have been falling over time (98) (i.e. “the soccer field is tilted downwards”). Injury-prevention epidemiologists have not addressed the fact that much of the fall in deaths/vkmt is derived from the protective values of lower travel speeds in increasingly congested urban areas (106), which offset higher speeds at other times. Vkmt is a parameter that disproportionately increases mainly from travel at very low speeds in so-called rush hours, and therefore its increase itself reduces risk. It is a paradox of road transport that its greatest successes in reducing deaths/vkmt result from its failures to provide high-speed travel (the idea that “no one is killed in a traffic jam”). Tracking CFR—which is not affected by vkmt—directly isolates the Newtonian relationships between increased speeds of impact and risks for death. These relationships are concealed partly by falling time trends in deaths/bvmkt from congestion and countermeasures. The equation $\Delta D = \Delta V^4 - \Delta(\text{Countermeasures} + \text{Congestion})$ summarizes these relationships.

The seventh barrier has been the compartmentalization of injury prevention and environmental protection. This compartmentalization has delayed recognition of the principle that speed control of motor transit is the sine qua non for self-sustainable transportation policies, which are friendly to the environment, promote safety, and protect public health (87). Lead, which was initially added to gasoline to increase driving speeds, produces community-wide emissions and subtle

neurotoxic impairment, especially in children (63a). Emissions of air pollutants increase exponentially with increases in travel speeds in private vehicles running on petrol (CO and NO_x) and in trucks and private vehicles running on diesel (PM₁₀). In Euro II petrol cars, raising travel speeds by a factor of 1.38, from 80 kph to 110 kph, raises emissions of CO and NO_x by factors of 3.5 and 1.7, respectively. In Euro II diesel cars, this same increase in speed increases emissions of PM₁₀ by a factor of 2.4. Emissions of CO₂, the gas that accounts for most of the greenhouse effects on global warming, increase arithmetically at speeds above 80 kph. The risks for death from road trauma from air pollution diverge sharply at speeds below 30–40 kph. In considering CO₂, CO, and hydrocarbons emitted by private vehicles and diesel trucks, there is an approximate U-shaped relationship between speed and fuel efficiency, which approaches maximum in the range of 40–75 kph (58, 81).

The eighth barrier is ideological objections to speed cameras. The pseudo conservative opposition is based on libertarian opposition to regulation, and fears of loss of privacy, and is similar to objections to gun control laws and compulsory seat belt use. The pseudo liberal opposition to regulation is based on the premise that it is the system and not the user that has to be fixed, and it opposes compulsory safety legislation as an infringement of civil rights (3, 54). Plowing the huge revenues from speed camera penalties back into road safety and transport and care for the disabled is the appropriate counterargument (45). But the most fundamental answer to these objections is that life and safety are the most basic of all human rights, and governments have a responsibility to protect these rights.

TOWARDS THE NEXT MILESTONE: PREDICTIVE MODELS OF ROAD DEATH AND INJURY

Using the accumulated knowledge on the effects of speed as part of a process of promoting health impact assessments, we propose the use of predictive models of risk for death, injury, and effects of air pollution and transportation disasters. We have used models based on traffic load, expected speeds, spillover, the Newtonian relationships between speed and injury in the Nilsson model, and the protective effects of speed control and congestion to predict the effects of such high-speed roads on road traffic tolls and air pollution from new high-speed highways (83). Preliminary data indicate that such a model anticipated increased speeds and death risks, currently 17 deaths/bvkm in a new high-speed toll road in Israel—fourfold that of the Autobahn and eightfold that of U.K. motorways.

DEVELOPING A SPEED-CONTROL STRATEGY

Given the huge toll in deaths, PYL, disability, and direct and indirect costs from road deaths, and the enormous benefits of speed control in reducing this toll, it follows that speed control, and speed-camera networks in particular—neglected

and rejected until now in the United States—need to become a central priority for injury prevention worldwide. The overriding effect of the exponential relationships between speed of impact and road deaths states the case for killing speed as the centerpiece of a strategy aiming for VZ. This strategy offers the potential for achieving major reductions in tolls from road crashes using existing state-of-the-art speed-camera and speed-calming strategies. We suggest that a policy of killing speed requires

- setting target goals based on reduction of deaths and injuries in absolute numbers and not merely deaths/bvkm; and
- promoting and implementing modal shifts from speed on roads to speed on rail and land use strategies which counteract urban sprawl;
- researching and developing vehicle designs with lower maximum speed limits and technologies that automatically restrict speed;
- developing and testing strategies for deployment of speed-camera networks that aim to shift the speed distribution of the entire population to the left, and not merely trap extremely high-risk subgroups;
- implementing international protocols for evaluation of the effectiveness of speed cameras and speed-calming measures;
- using technologies that exploit time-interval points to monitor average speeds; and
- using “out-of-the box” solutions, such as speed chips in vehicles of young drivers which transmit information on vehicle speed to the parent’s cellular telephone (i.e., risk identification and prevention in the highest risk group— young drivers—targeted at the market to whom it matters most: their parents).
- Developing systems to monitor speed-gating—i.e., speeding and tailgating (headway interval)— and speed regulating systems activated by shortened headways at high speeds (78).

Australia, notably Victoria, and the United Kingdom have led the way in achieving abrupt, large, and sustained reductions in road death tolls from strategies heavily emphasizing speed control from speed-camera networks and speed calming. Victoria’s aim is not only to reduce speeds of drivers whose vehicles exceed speed limits, but also to shift the entire curve of speed distribution downward to the left. We predict that in the United States, road-injury prevention efforts will continue to drift, and death tolls will not drop as long as upward speed creep continues to negate the protective benefits of vehicle- and road-based countermeasures and congestion. But even speed cameras may not be able to offset the risks from speed creep from higher speed limits.

The data on reductions in death tolls from speed-camera networks and speed calming mean that it is no longer ethically or scientifically excusable to conceal the failure to reduce deaths tolls in absolute numbers behind the figleaf of falling trends in deaths/bvkm. Without implementation and enforcement of speed-control

measures, it will be impossible to abort the huge rise in road death tolls worldwide as car use increases explosively.

The failures of speed control, especially in the United States, result from a flawed ethical paradigm in which intangibly defined gains from saving time and marketing of the thrill of speed result in tolerating large losses of human life. To counteract this flawed paradigm, there is a need for Code of Helsinki-type requirements (80) mandating review by public health authorities of decisions to increase or decrease speeds and speed limits. Such social decisions, made outside the medical setting, have major health impacts and should therefore be subject to the same kinds of review to which medical experiments are subject. Progress towards VZ—no road deaths—should be the standard by which success or failure in road-injury prevention is measured. Ironically, there is little pressure for the most obvious measures, i.e, designing vehicles with lower maximum speed, along with speedometers that do not waste half their space displaying illegal speeds.

Those who permit speed creep to progress ignore the Newtonian message from the Biblical story of Joshua at Gibeon. Right after God answered Joshua's request to temporarily suspend Newtonian laws of motion and energy, the Bible warned that such miracles would never recur. Our review suggests that the cost of ignoring this message in the United States may be as high as 20,000 lives lost per year.

ACKNOWLEDGMENTS

This work was supported in part by grants from the British Friends of the Hebrew University, anonymous donors, and the European Union 6th Framework Network for Advanced Passive Safety. We thank Metuna (<http://www.metuna.org.il>) for encouragement and support.

Appendix 1: Selected Websites with information on Speed Control and Speed Cameras*

Australian Road and Traffic Authority and ARRB	http://www.rta.nsw.gov.au/roadsafety/speedandspeedcameras/ http://www.policesspeedcameras.info/ Speed Enforcement in Australia
US Insurance Institute of Highway Safety	http://www.iihs.org/safety_facts/qanda/speed_lawenf.htm
UK Department of Transport	http://www.dft.gov.uk/stellent/groups/dft_rdsafety/documents/divisionhomepage/030766.hcsp
Norway Transport and Communications	http://odin.dep.no/sd/engelsk/028001-120004/dok-bn.html
National Camera Safety Liaison	http://www.nationalsafetycameras.co.uk/
Safespeed	http://safespeed.org.uk
Slower Speeds Initiative	http://www.slower-speeds.org.uk/
TRL, Transport Research Laboratory	http://www.trl.co.uk

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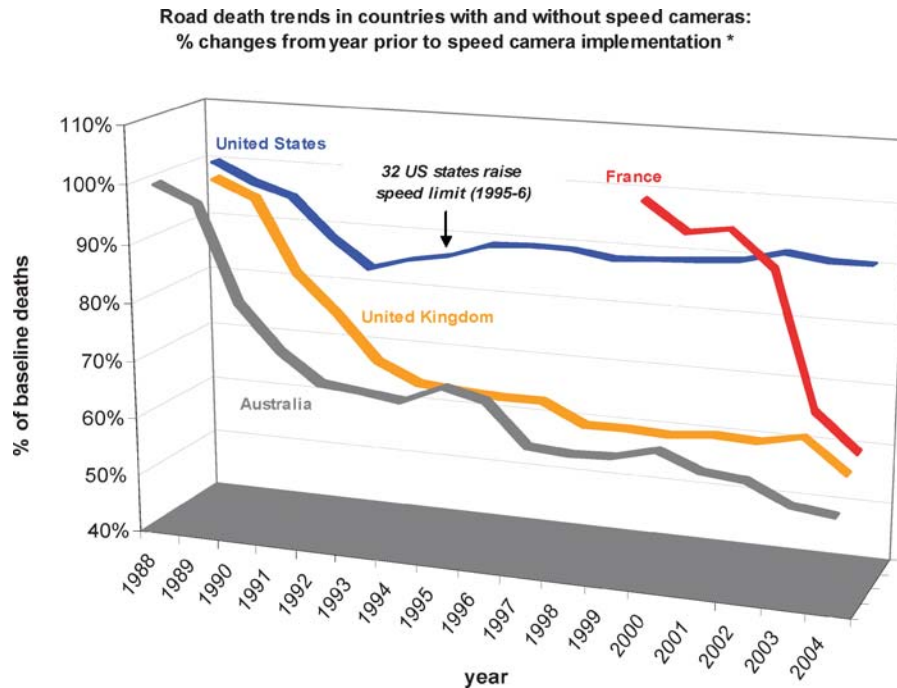


Figure 4 Road death trends in countries with and without speed cameras: % change from year prior to speed camera implementation, except for the United States, where no speed camera program has been implemented. Baseline number of deaths: France (8487), Australia (2887), United Kingdom (5373), United States (47,087). Speed cameras, along with speed calming, were introduced in Australia, the United Kingdom, and France in 1989, 1990, and 2000, respectively. Figure based on data from References 5, 25, 63, and 103.