# Causal Determination in Road Accidents: <br> An Application of the Halpern/Pearl Notion of 'Actual Cause' 

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#### Abstract

Determining whether or not an event was a cause of a road accident often involves determining the truth of a counterfactual conditional, in which what happened is compared to what would have happened had the putative cause been absent. Using structural equation models, Pearl and his associates have recently developed a rigorous method for posing and answering causal questions, and this approach is especially well-suited to the analysis of road accidents. Following a general discussion of causal analysis, we apply these methods to a freeway rear-end collision. The results suggest that not only were the actions of the drivers actually involved in the collision causes of the accident, but so were the actions of drivers ahead of them.


## Introduction

Although the costs and consequences of any particular road accident rarely approach those that occur in aircraft or rail accidents, the sheer number of road accidents occurring in a given year means that their total costs usually outstrip those from accidents in other modes. A road accident may be investigated by the police, in order to assess the possibility of criminal liability, by an accident investigator retained by a party involved in civil proceedings, by a governmental agency seeking to identify actions which could prevent similar accidents in the future, or by researchers seeking to advance our understanding of how and why accidents occur. All these investigative activities share a common concern however, to identify those events that could be considered as causes of the accident. For example, the Uniform Vehicle Code [10]states that to be guilty of vehicular homicide a driver must have been "engaged in the violation of any state law or municipal ordinance," and that "such violation is the proximate cause of said death." In tort law, "The most basic element of any tort cause of action is some causal connection between the act or omission of the tortfeasor and the plaintiff's injury" [6]. A main objective of an investigation by the National Transportation Safety Board (NTSB) is a statement of the "probable causes" of an accident, while the objective of the Tri-Level study was to provide "up to date data regarding traffic accident causation" [12].

Causal Concepts

Baker [1] has noted that causal attributions in road safety take a number of forms, and are often invoked to achieve rhetorical, rather than scientific, objectives. He has also given an often-used definition of "causal factor" as a circumstance "contributing to a result without which the result could not have occurred." This definition is (not by accident) similar to definitions of cause used in other types of accident investigation. For instance, Miller [9] points out that in a definition used by the NTSB, a "condition or event" qualifies as a probable cause of an accident if "had the condition or event been prevented...the accident would not occur," while the Air Force has used "A cause is an act, omission, condition, or circumstance which if corrected, eliminated, or avoided would have prevented the mishap." These definitions in turn share content with the legal notion of "cause in fact," where for an event to be considered as a cause it must satisfy a "but for" test, that is, "defendant's conduct is not a cause of the event, if the event would have occurred without it" [6].

Implicit in these ideas is first, that removal of a cause should be sufficient to prevent the result, and second that one determines whether or not a circumstance is a cause by carrying out a counterfactual test, where what happened is compared to what would have happened had the circumstance been absent. In practice however giving a rigorous yet general specification for such tests has proved somewhat daunting, the main challenge being to unambiguously specify what should count as the counterfactual condition. Since one can, with sufficient imagination, almost always describe a number of different scenarios where an accident is avoided, this test condition should involve a change that is in some sense minimal. Lewis [8] has given a philosophical treatment of truth conditions for causal assertions using a comparison between what actually happened and what happens in a closest possible world where certain counterfactual assertions are true. What is meant by "closest possible world" is left deliberately vague, which improves the generality of Lewis' treatment but makes it difficult to apply to practical cases. Over the past 15 years or so however, there has been increased interest in causal inference as a component of artificial intelligence, and one especially useful approach is based on what Pearl [11] calls a "causal model." This consists of a set of exogenous variables, a set of endogenous variables, and for each endogenous variable a structural equation describing how that variable changes in response to changes in the exogenous and/or other endogenous variables. Events are defined in terms of values taken on by the model's variables, and the closest possible world where a set of variables takes on (counterfactual) values can be unambiguously defined as the outcome of a modified causal model, where the exogenous variables are set to the same values as in the actual condition, but where the structural equations associated with the counterfactual event are replaced by assignment statements. Pearl goes on to describe how when the evidence about an event is not sufficient to uniquely identify the values taken on by each exogenous variable (i.e. to identify which possible world is the actual world) uncertainty can be accommodated by first placing a prior probability distribution over the causal model's exogenous variables and then using Bayesian updating to compute the posterior distribution given the evidence at hand. The probability attached to an assertion, either indicative or counterfactual, is then simply the posterior probability assigned to the set of possible worlds where that assertion is true. More recently, Halpern and Pearl [5] have extended these ideas and defined an "actual cause" as an event satisfying a "but for" test along with additional conditions which deal with some counterintuitive consequences of simple "but for" tests.

## Application to Freeway Rear-ending Collisions

Over the past several years we have been applying Pearl's approach to the analysis of road accidents, with an emphasis on determining the degree to which excess speed could be considered a causal factor. Descriptions of some of this work can be found in [3,4]. In this paper though we would like to describe some preliminary results from an ongoing study of freeway rear-ending accidents. Although such accidents do not usually result in fatal or even very severe injuries, they are responsible for a substantial fraction of the unpredictable delays many of us now regard as unavoidable aspects of urban life. Frequently, such accidents occur when a platoon of vehicles successively brake and the braking deceleration of at least one vehicle is not sufficient to prevent it from colliding with the vehicle ahead. Reducing the frequency of such collisions, for example by improving the competency of drivers or deploying in-vehicle collision avoidance technology, could then be one way to reduce travel delay without resorting to expensive additions to highway capacity. In Minnesota, as is many other places, it is recommended that drivers maintain following headways of at least 2.0 seconds, and responsibility for a rear-end collision is generally attributed to the following vehicle actually involved in the collision. If however the actions of drivers earlier in the sequence also contribute to the collision, this method of giving feedback will leave these earlier drivers unaware of their contribution, and so be of limited effectiveness. But how can we assess the causal contributions, if
any, of these other drivers?
These concerns are not new, and Brill [2] has described a relatively simple kinematic model of successive braking which applies to the problem at hand. Imagine a platoon of vehicles, indexed in order from first to last, by $k=1, . ., n$, and let $\mathrm{v}_{1}, \mathrm{v}_{2}, \ldots \mathrm{v}_{\mathrm{n}}$ denote their speeds. At time $\mathrm{t}=0$ the lead driver brakes to a stop, with deceleration $a_{1}$, and after a reaction time $r_{2}$ driver 2 also brakes to stop, with deceleration $\mathrm{a}_{2}$, and so forth. A rear-end collision between vehicles k and $\mathrm{k}+1$ will be avoided as long as the distance needed by driver $\mathrm{k}+1$ to stop does not exceed the available stopping distance. That is,

$$
\begin{equation*}
x_{k+1}+\frac{v_{k}^{2}}{2 a_{k}} \geq r_{k+1} v_{k+1}+\frac{v_{k+1}^{2}}{2 a_{k+1}} \tag{1}
\end{equation*}
$$

where $\mathrm{x}_{\mathrm{k}+1}$ is the distance separating vehicle k 's rear bumper from vehicle $\mathrm{k}+1$ 's front bumper. Letting $\mathrm{x}_{\mathrm{k}+1}=\mathrm{v}_{\mathrm{k}+1} \mathrm{~h}_{\mathrm{k}+1}$ express this distance in terms of driver $\mathrm{k}+1$ 's speed and following headway, driver $\mathrm{k}+1$ will stop before colliding if his or her deceleration satisfies

$$
\begin{equation*}
a_{k+1} \geq \frac{v_{k+1}^{2}}{\frac{v_{k}^{2}}{a_{k}}+2 v_{k+1}\left(h_{k+1}-r_{k+1}\right)} \tag{2}
\end{equation*}
$$

Relation 2 has some interesting implications. Other things equal, the minimum deceleration required of driver $\mathrm{k}+1$ increases as the deceleration used by driver k increases, since $\mathrm{k}+1$ 's available stopping distance decreases as $a_{k}$ increases. Also, other things equal, the minimum deceleration required by driver $k+1$ increases as the difference between $k+1$ 's following headway and reaction time $\left(h_{k+1}-r_{k+1}\right)$ decreases. Together these features imply, as Brill pointed out, that if each driver in the platoon is a little slow in reacting, so that his or her reaction time is longer than the following headway, the minimum required deceleration will tend to increase for each succeeding vehicle. If the platoon is long enough a collision can become inevitable. In this case, it would appear reasonable to attribute the accident to the actions of each driver in the platoon, rather than to an egregious lapse by the last driver.

To illustrate how Halpern and Pearl's notion of actual cause might be applied to a freeway rear-end crash consider Figure 1, which displays Brill's sequential braking model (in this case involving a three-vehicle platoon) as a directed acyclic graph. The nodes of the graph represent the model's variables while the arrows indicate the presence and direction of causal dependencies. Those nodes without arrows pointing toward them (such as $\mathrm{v}_{1}$ ) represent exogenous variables, while the others (such as $\mathrm{a}_{20}$ ) represent endogenous variables. To complete the model we need to specify, for each endogenous variable, a structural equation. The variables $\mathrm{a}_{20}$ and $\mathrm{a}_{30}$ are the minimal decelerations needed, for vehicles 2 and 3 respectively, to stop before colliding with the vehicle ahead, and these are determined from the right-hand side of relation 2 . We assume that the actual decelerations are then determined as

$$
\begin{equation*}
\mathrm{a}_{\mathrm{k}}=\min \left(\mathrm{a}_{\mathrm{k} 0}+\mathrm{u}_{\mathrm{k}}, a\right) \tag{3}
\end{equation*}
$$

where $a$ is a maximum achievable deceleration, and $u_{k}$ is an exogenous term which accounts for the difference between observed and minimum deceleration. Finally, the variable y is a collision indicator, and is assumed to be determined via

$$
\begin{equation*}
\mathrm{y}=0, \text { if } \mathrm{a}_{30}[a \tag{4}
\end{equation*}
$$

$$
1, \text { if } \mathrm{a}_{30}>a
$$



Figure 1 - Directed Acyclic Graph Representation of Three-Vehicle Platoon Collision Model.

For example, suppose $\mathrm{v}_{1}=\mathrm{v}_{2}=\mathrm{v}_{3}=12.2$ meters $/ \mathrm{sec}$, that the maximum achievable deceleration is $a=6.1$ meters $/ \mathrm{sec}^{2}$, and that driver 1 brakes to a stop with $\mathrm{a}_{1}=1.5$ meters $/ \mathrm{sec}^{2}$. Suppose also that $\mathrm{h}_{2}=2$ seconds but $r_{2}=4$ seconds, so that by relation 2 driver 2 's minimum deceleration is $\mathrm{a}_{20}=3.0$ meters $/ \mathrm{sec}^{2}$. Driver 2 then decelerates at 3.2 meters $/ \mathrm{sec}^{2}$ (which means that $\mathrm{u}_{2}=0.2 \mathrm{~meters} / \mathrm{sec}^{2}$ ), but suppose driver 3 is tailgating a bit, with $h_{3}=1.5$ seconds, and reacts after $r_{3}=2.5$ seconds. The minimum deceleration for driver 3 is then $\mathrm{a}_{30}=6.7$ meters $/ \mathrm{sec}^{2}$, which exceeds the maximum deceleration $a=6.1$ meters $/ \mathrm{scc}^{2}$, and a rear-end collision between vehicle 2 and vehicle 3 occurs. Driver 3's tailgating can be considered an actual cause of this collision, since if we counterfactually set $h_{2}=2.0$ seconds but fix $v_{2}, a_{2}$ and $v_{3}$ at their actual values, the minimum deceleration needed by driver 3 falls to $\mathrm{a}_{30}=4.3$ meters $/ \mathrm{sec}^{2}$, and the collision is avoided. But driver 2's long reaction time is also an actual cause of the collision, since setting $r_{2}=2.5$ seconds, but keeping $\mathrm{u}_{2}=0.2 \mathrm{~meters} / \mathrm{sec}$, leads to $\mathrm{a}_{30}=2.7$ meters $/ \mathrm{sec}^{2}$.

## An Actual Collision

Do similar things happen in reality? As part of an ongoing study, permanently mounted video cameras were installed on high-rise buildings adjacent to an urban freeway in Minnesota. The cameras were connected to a computer that recorded the weekday traffic movements from the early morning rush hour to the early evening. Video records were saved in one-hour segments on the computer's hard drive. Accident reports filed with the State Patrol along with incident reports recorded by the Minnesota Dept. of Transportation's Traffic Management Center were then used to determine which video segments might contain accident footage.

The computer program VideoPoint was used to extract the screen coordinates of vehicles from a frame of the recorded video by clicking on a discernable point on the object of interest. The program then advances the movie one frame and the process is repeated, so by successively clicking on the
same point of a vehicle's image it was possible to record the sequence of coordinates representing the vehicle's trajectory. Standard photogrammetry transformations were then used to convert the screen coordinates to the corresponding real-world coordinates. Figure 2 shows the trajectories of a platoon of seven vehicles involved in sequential braking maneuvers, recorded during an afternoon peak period, where the seventh vehicle was observed colliding with the sixth.

To assess the possible causal contributions of the drivers in this platoon, it was first necessary to determine values for the individual speeds, decelerations, reaction times and following headways. During the time before a vehicle began braking it was assumed that the vehicle traveled at a constant speed, and visual examination of the position-time diagram shown in Figure 2 supports this assumption. Each vehicle speed was then determined by fitting a linear regression line to the initial portion of its trajectory data and determining the slope of this best fitting line.

When braking began, it was assumed that each driver decelerated with the intention to stop. It was also assumed that the deceleration was constant over the braking period. This allowed a fairly straightforward determination of the decelerations, headways, and reactions times from the trajectories shown in Figure 2. The motion of each vehicle can be described using a two-part relation, where the first part gives the vehicle's trajectory before braking and the second part describes the distance traveled during braking. That is,

$$
\begin{array}{ll}
\mathrm{z}_{\mathrm{k}}(\mathrm{t})= & \mathrm{v}_{\mathrm{k}} \mathrm{t}, \mathrm{t}\left[\mathrm{t}_{0 \mathrm{k}}\right.  \tag{5}\\
& \mathrm{v}_{\mathrm{k}} \mathrm{t}-0.5 \mathrm{a}_{\mathrm{k}}\left(\mathrm{t}-\mathrm{t}_{0 \mathrm{k}}\right)^{2}, \mathrm{t}>\mathrm{t}_{0 \mathrm{k}} .
\end{array}
$$

where $\mathrm{t}_{0 \mathrm{k}}$ is the time at which driver k began braking. Determining $\mathrm{t}_{\mathrm{k}}$, and the deceleration $\mathrm{a}_{\mathrm{k}}$ was accomplished by minimizing the sum of squared errors between the measured position value and the position value estimated using equation 5 .

The term 'space headway' is used to describe the distance between two successive vehicle front ends at the instant the leading vehicle begins braking. These values were determined from the Figure 2 trajectories using the braking times estimated as described above, as depicted in Figure 3. Space headways were then converted to separation distances by subtracting a value of 4.6 meters for the effective length of the vehicle, and these were in turn converted into separation headways ( $\mathrm{h}_{\mathrm{k}}$ ) by dividing by the speed of the following vehicle. Finally, reaction times were defined as the difference in time between when the leading vehicle began to brake and the time when the following vehicle began to brake, and Figure 4 illustrates how these were determined from the vehicle trajectories. The results of the data extraction are displayed in Table 1.


Figure 2 - Trajectories of Vehicles Involved in Actual Collision x -axis is in seconds, y -axis is in feet.


Figure 3 - Example of Space Headway Determination $x$-axis is in seconds, $y$-axis is in feet.


Figure 4 - Example of Reaction Time Determination
$x$-axis is in seconds, $y$-axis is in feet.

## 'Actual Cause' Analysis

The entries in Table 1 tell an interesting story. Driver 1 braked to a stop with a deceleration of 2.1 meters $/ \mathrm{sec}^{2}$, and about 1.5 seconds later driver 2 braked with a deceleration of about $1.8 \mathrm{~meters} / \mathrm{sec}^{2}$. It was possible for driver 2 to decelerate less rapidly than driver 1 because 2's following headway, at 1.7 seconds, was longer than 2's reaction time. Driver 3 on the other hand needed almost 4 seconds to react, and although 3 's following headway was roughly equal to the recommended minimum of 2.0 seconds, 3 's minimum deceleration jumped to about 3.7 meters $/ \mathrm{sec}^{2}$, with an actual deceleration of 4.1 meters $/ \mathrm{sec}^{2}$. Drivers 4 and 5 also had reaction times longer than their following headways, though the differences were not as extreme as 3 's, so the minimum and actual braking decelerations continued to increase. Driver 6 was a bit more on the ball, but was traveling a bit faster than driver 5, and so the minimum deceleration increased again. When we come to driver 7 , whose reaction time was about 0.5 seconds longer than his/her headway, the minimum deceleration jumped to 6.7 meters $/ \mathrm{sec}^{2}$, which exceeds the 5.8 meters $/ \mathrm{sec}^{2}$ observed to have been used by driver 7 .

Table 1 - Values of Vehicle and Driver Variables for Seven-Vehicle Platoon.

|  | Variable Values |  |  |  |  |  |
| :--- | :--- | :--- | :--- | :--- | :--- | :--- |
| Vehicle | $\mathbf{v}_{\mathbf{k}}(\mathbf{m} / \mathbf{s})$ | $\mathbf{h}_{\mathbf{k}}(\mathbf{s e c})$ | $\left.\mathbf{r}_{\mathbf{k}} \mathbf{( s e c}\right)$ | $\mathbf{a}_{\mathbf{k}}\left(\mathbf{m} / \mathbf{s}^{\mathbf{2}}\right)$ | $\mathbf{a}_{\mathbf{k} \mathbf{0}}\left(\mathbf{m} / \mathbf{s}^{\mathbf{2}}\right)$ | $\mathbf{u}_{\mathbf{k}}\left(\mathbf{m} / \mathbf{s}^{\mathbf{2}}\right)$ |
| 1 | 14.97 | -- | -- | 2.08 | -- | -- |
| 2 | 14.29 | 1.69 | 1.46 | 1.82 | 1.77 | 0.05 |
| 3 | 13.24 | 2.0 | 3.97 | 3.24 | 2.62 | 0.62 |
| 4 | 13.07 | 1.95 | 2.25 | 4.11 | 3.69 | 0.42 |
| 5 | 12.30 | 1.22 | 1.38 | 4.27 | 4.04 | 0.23 |
| 6 | 13.16 | 1.15 | 1.01 | 4.55 | 4.43 | 0.12 |
| 7 | 12.91 | 1.28 | 1.79 | 5.82 | 6.68 | -- |

So who was responsible for this collision? Starting with driver 7, it is straightforward to verify that if 7 had had a following headway of 2.0 seconds, using the measured values for his/her speed and reaction time and driver 6's speed and deceleration, then 7's minimum deceleration drops to about 3.8 meters $/ \mathrm{sec}^{2}$. Since this is substantially lower than 7 's observed deceleration of 5.8 meters $/ \mathrm{sec}^{2}$, we can conclude that driver 7's failure to observe the recommended following rule was an actual cause of the collision. But now let's look at driver 3. His or her reaction time was clearly long compared to what other drivers in the platoon appeared capable of, and we can ask whether or not this long reaction time might also have been an actual cause. Setting 3's reaction time to the counterfactual value of 2.5 seconds, leaving all observed speeds and headways, and all other observed reaction times alone, and then computing the actual decelerations for drivers 4,5 , and 6 by adding the observed differences $u_{k}$ to the new computed minimums, produces a counterfactual minimum deceleration for driver 7 of about 3.9 meters $/ \mathrm{sec}^{2}$. Since this is also substantially lower than driver 7 's observed deceleration, we can say that driver 3's long reaction time was also an actual cause. Next, looking at Table 1, we can see that both driver 4 and driver 5 also had observed reaction times that were longer than their headways, and we can ask whether or not these might also be considered causes of the collision. Separately setting the reaction times of drivers 3,4 and 5 to their observed headways produced minimum decelerations for driver 7 of $3.5 \mathrm{~meters} / \mathrm{sec}^{2}$, $5.5 \mathrm{~meters} / \mathrm{sec}^{2}$, and 5.9 meters $/ \mathrm{sec}^{2}$, respectively. Finally, if drivers 3,4 , and 5 all had reaction times equal to their observed headways, the minimum deceleration for driver 7 would fall to $3.0 \mathrm{~meters} / \mathrm{sec}^{2}$.

## Conclusion

It has been observed that at night drivers sometimes 'overdrive' their headlights, in that the stopping distances for their chosen speeds exceed the distances they can see ahead. The above results suggest that in congested conditions freeway drivers on occasion overdrive their reaction times, in the sense that their reaction times tend to be longer than their following headways. At least for this example, this over-driving appears to be locally benign, because based on what the vehicle ahead is doing and on an expectation that if the driver ahead does brake the deceleration will not be too extreme, then sufficient time to slow or stop is still available. What Brill's relation 2 shows though is that when each of a platoon of drivers overdrives their reaction times, this expectation of relatively gentle deceleration by the vehicle ahead can break down, so that in congested conditions prevention of rearend collisions can require that drivers base their decisions on more than local information. Brill's effect can also be interpreted as resulting from the action of external costs. An over-driver will gain the benefits of his or her individual action (whatever those might be), while the costs of that action will tend to fall disproportionately on following drivers. This suggests that over-driving in congested conditions will be "consumed" at levels exceeding what is socially optimal. As with other situations involving external costs, achieving a socially optimal decision would then require some form of coordination mechanism.

More generally, Kletz [7] has argued that effective prevention of accidents not only requires identifying immediate causes, but also avoiding the accident by identifying those more distant causes that created the conditions making the accident possible. But determining whether or not an event qualifies as a cause requires a counterfactual test, and rational discussion can break down when different parties implicitly compare the actual to different "closest possible worlds." When the underlying mechanisms governing the accident process can be expressed as structural equations, Pearl has shown how to unambiguously define truth conditions for causal assertions, in a form that can be readily applied to actual cases.

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