Pedestrian/Car Accident

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This example is taken from the book Technische Analyse von Verkehrsunfällen anhand von Beispielen, but the analysis is my own and somewhat different from the analysis in the book.

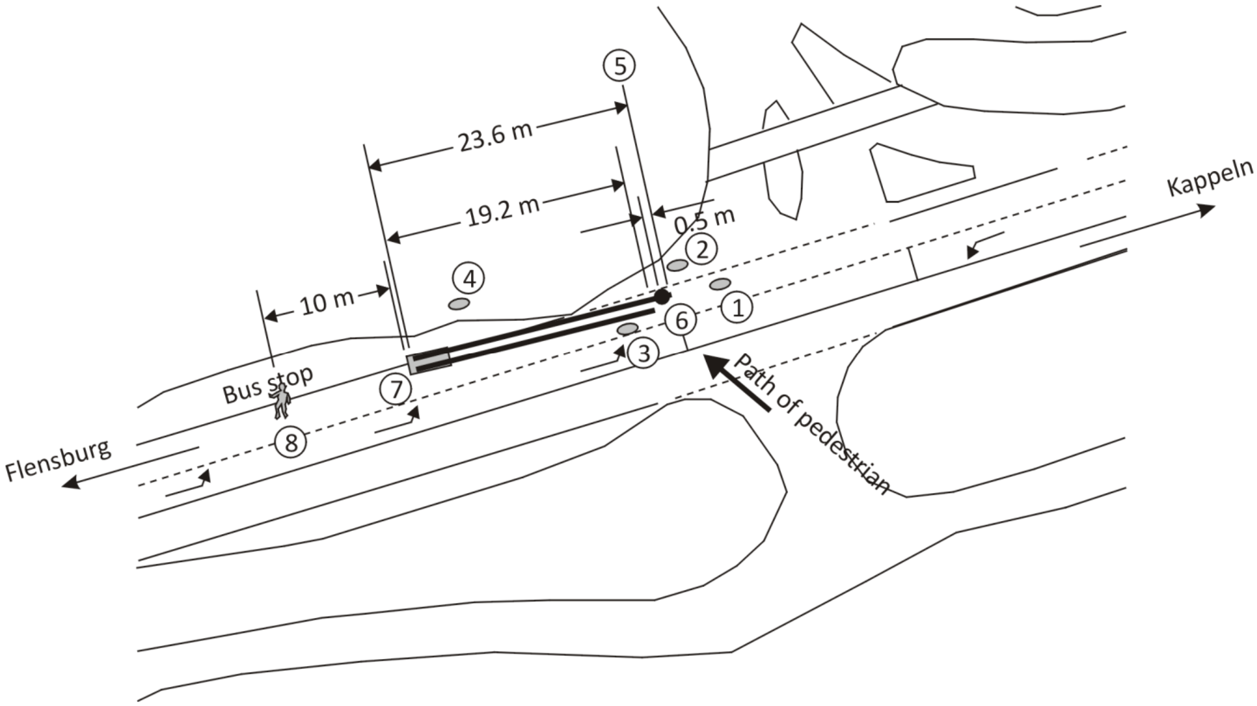
Events

This study involves the collision of an automobile with a pedestrian. It occurred between Kappeln and Flensburg, Germany on the B199 highway during the evening of 2 January 1992. The pedestrian, a woman aged 47, crossed the divided, 2-lane highway in order to catch a bus, headed toward Flensburg. She was struck by a car on the left side of the car, pretty much directly in front of the driver. The driver, aged 24, was accompanied by his fiancée, aged 23. The pedestrian was struck by the front bumper of the car, then fell onto the hood of the car, also breaking the windshield and damaging the roof of the vehicle just above the driver. She was severely injured in the accident, suffering fractures of her legs and arms and severe injuries to her head. Neither alcohol nor drugs was involved in the accident.

The pedestrian was accompanied by a friend, 52, who said they were going to take the bus to Flensburg. This witness said her friend walked ahead of her and was reaching and searching in her purse for a flashlight as she crossed the road.

The fiancée of the driver estimated that they were travelling at between 70-80 kph. At this section of highway the speed limit is 100 kph. She claimed they were driving a great deal under the speed limit because the road is curvy, and her fiancée knows that she gets nervous driving on this road at night.

Figure 1 – Intersection where accident occurred



1) Piece of flashlight
2) Pedestrian's cap
3) Piece of car license plate
4) Flashlight
5) Start of car skid marks
6) Thickening of skid marks at this location
7) Final location of car
8) Final location of pedestrian

Figure 2 – Diagram of accident scene

The car involved was a small, 1984 Ford Kombi (station wagon). It was travelling toward the left in the diagram above. It struck the pedestrian and launched her forward. The car continued to brake and skid until it came to a stop just next to the bus stop. The victim wound up lying cross-way to the direction of the car, 10 m in front of the final location of the stopped car. The road surface was dry asphalt. As stated, the accident took place after dark. The pedestrian was dressed in dark clothes.

Another partial witness to the accident was the bus driver of the bus travelling to Flensburg. He was driving the bus at some distance behind the Ford and saw the brake lights illuminate. He slowed and stopped the bus prior to entering the accident scene. It is possible that the pedestrian was fishing around in her purse for the flashlight so that she could signal the bus to stop, was not paying attention closely, so did not see the car in front of the on-coming bus. She may also have been hurrying across the highway as shown so that she would not miss the bus. Just before being hit, she called out to her friend, "Irma, a car! Man!"

The skid marks of the car are as shown. A little past the start of the skid marks (0.5 m after they start), there is a perceptive, but momentary, thickening of the skid marks.

Analysis

This accident involves a frontal collision between a car and a pedestrian. The sequence of events is as follows:

1. Driver sees pedestrian
2. Driver starts braking
3. Brakes lock and car skids
4. Front bumper of car strikes pedestrian's legs
5. Pedestrian falls onto the hood of the car and is launched forward
6. Car continues to skid until it comes to a stop

Events 4 and 5 could actually occur before 1, 2, or 3. Part of the analysis is to determine the sequence of these six events. For example, the driver could have struck the pedestrian prior to braking if he had not seen her until too late. The German court was interested in determining whether or not the accident could have been avoided had the driver reacted in timely manner. Therefore my analysis breaks the series of events down into a spatial and also a temporal sequence, describing what happened, when it happened, and where along the accident path each event occurred.

Skidding time

The time and distance that the car skid after the brakes locked is obvious from the skid marks. The skid marks of the right-hand tires are 23.6 m, and those of the left tires are 19.2 m. This difference can be accounted for simply by differences in the drag factor on the tires due to different pavement conditions on the edge and in the center of the highway. We shall use the longer distance in our calculations, since once the right-hand tires were locked, the left-hand tires must have been on the verge of locking. We shall use a friction coefficient of 0.8 for dry, asphalt pavement. Imposing equilibrium on the skidding vehicle

$$F = m \cdot a = f \cdot m \cdot g$$

$$a = f \cdot g = 0.8 \cdot 9.81\ m/sec^2 = 7.85\ m/sec^2$$

in the direction opposite the vehicle's velocity. To get the velocity at the start of skidding, use

$$-7.85\frac{m}{sec^2} \cdot \int_0^{23.6m} dx = \int_{v3}^{0} v \cdot dv$$

$$-\frac{1}{2}v_3^2 = -7.85\frac{m}{sec^2} \cdot 23.6\ m$$

$$v_3 = \sqrt{2 \cdot 7.85 \cdot 23.6}\ m/sec = 19.2\ m/sec = 69.3\ kph$$

The duration of this phase can be determined from

$$a = \frac{dv}{dt}$$

$$\int_{v3}^{v6} dv = \int_{t3}^{t6} a \cdot dt$$

If we let the start time, t_3, be 0, and the end velocity, v_6, is 0, then

$$-v_3 = a \cdot t_6$$

$$t_6 = \frac{-v_3}{a} = \frac{-19.2\ m/sec}{-7.85\ m/sec^2} = 2.45\ sec$$

Contact point with pedestrian

At a point 0.5 m into the start of the skid marks, there is a temporary thickening of the skid marks. Initially when the car bumper strikes the legs of the pedestrian, there is no sudden vertical load that would cause this thickening. There is a sudden vertical load that would cause this when the pedestrian lands on the car hood. Basically the car struck the pedestrian, knocked her legs out from under her, and then she landed on the hood of the car. She then moved along the hood surface, contacted the windshield with her head and upper body, and was launched from this point to where she finally landed. Thus this thickening can be taken to be her original location before the car drove up under her. The car struck her first when the front bumper was at the location of the thickened skid mark. The overhang of the car bumper in front of the front wheels is 0.75 m. Thus it appears that the car struck the pedestrian just before the brakes locked, where the wheels were 0.25 m to the right of the start of the skid marks, during the pre-skidding phase.

Pre-skidding phase

It is a well-known phenomenon that a driver who encounters an unexpected obstacle does not apply full braking right away. From demonstrated reaction tests, the driver will first brake for about 0.2 sec at a lower rate before applying full braking. Thus, prior to full braking, we will include a 0.2 sec phase at half braking. So the speed at the start of this half-braking phase, v_2, can be estimated to be

$$a = \frac{dv}{dt}$$

$$\int_{v2}^{v3} dv = \int_{t2}^{t3} a \cdot dt$$

$$v_3 - v_2 = a \cdot (t_3 - t_2)$$

$$v_2 = v_3 - a \cdot (t_3 - t_2) = 19.2 \frac{m}{sec} + \frac{7.85}{2} \frac{m}{sec^2} \cdot 0.2\ sec = 20.0\ m/sec = 72.1\ kph$$

This will also be v_1, since between perception of the pedestrian and the driver's response, there is no braking.

To lay-out completely the sequence of events, we need also to calculate the location of the car when the driver first applied the brakes.

$$\int_{x2}^{x3} a \cdot dx = \int_{v2}^{v3} v \cdot dv$$

$$a \cdot (x_3 - x_2) = \frac{1}{2}(v_3^2 - v_2^2)$$

$$(x_3 - x_2) = \frac{1}{2 \cdot a}(v_3^2 - v_2^2) = \frac{2}{2 \cdot -7.85} \frac{sec^2}{m}\left[\left(19.2\frac{m}{sec}\right)^2 - \left(20.0\frac{m}{sec}\right)^2\right] = 3.93\ m$$

Thus the half-braking phase starts 3.93 m to the right of the start of the skid marks.

As was determined above, the car's front bumper contacts the pedestrian's legs during this phase, in fact 0.25 m before the end of this phase. The velocity of the car at this contact point can be calculated from

$$\int_{x2}^{x4} a \cdot dx = \int_{v2}^{v4} v \cdot dv$$

$$a \cdot (x_4 - x_2) = \frac{1}{2}(v_4^2 - v_2^2)$$

$$v_4 = \sqrt{2 \cdot a \cdot (x_4 - x_2) + v_2^2} = \sqrt{2 \cdot \left(\frac{-7.85\frac{m}{sec^2}}{2}\right) \cdot 3.68\ m + (20.0\ m/sec)^2}$$

$$v_4 = 19.3\ m/sec = 69.5\ kph$$

The time to cover the distance from the start of the pre-skidding phase is

$$\int_{v2}^{v4} dv = \int_{t2}^{t4} a \cdot dt$$

$$v_4 - v_2 = a \cdot (t_4 - t_2)$$

$$t_4 - t_2 = \frac{v_4 - v_2}{a} = \frac{(19.3 - 20.0)\ m/sec}{\left(-\frac{7.58}{2}\right)\frac{m}{sec^2}} = 0.19\ sec$$

The same calculation can be performed to determine the time and velocity of event 5 above, displacing it from the start of skidding, event 3.

$$v_5 = \sqrt{2 \cdot a \cdot (x_5 - x_3) + v_3^2} = \sqrt{2 \cdot \left(-7.85\frac{m}{sec^2}\right) \cdot 0.5\ m + (19.2\ m/sec)^2}$$

$$v_4 = 19.0\ m/sec = 68.5\ kph$$

$$t_5 - t_3 = \frac{v_5 - v_3}{a} = \frac{(19.0 - 19.2)\ m/sec}{(-7.85)\frac{m}{sec^2}} = 0.026\ sec$$

Pre-braking phase

Reaction times vary when observing obstructions while driving, depending heavily on the contrast between the obstruction and its background. In the case of low light and a dark-clad pedestrian, the average reaction time lies between 1.0-1.1 sec. This is the time that it takes for the driver to perceive the situation, formulate a response, and give this response. Thus, using a reaction time of 1.05 sec, we can calculate the location of the car when the driver first saw the pedestrian.

$$\int_{x1}^{x2} dx = \int_{t1}^{t2} v \cdot dt$$

$$(x_2 - x_1) = v \cdot (t_2 - t_1) = 20.0 \frac{m}{sec} \cdot 1.05\, sec = 21.0\, m$$

Spatial and temporal reconstruction of events

Table 1 gives a synopsis of the likely chain of events that occurred during the course of the collision with the pedestrian.

Event	Location	Time	Velocity	Description
1	0 m	0 sec	72.1 kph	Driver of Ford Kombi first notices pedestrian
2	21.0 m	1.05 sec	72.1 kph	Driver reacts and begins half-braking
3	24.7 m	1.24 sec	69.5 kph	Car's front bumper strikes pedestrian's legs
4	24.9 m	1.25 sec	69.3 kph	Driver begins full braking, car skids
5	25.4 m	1.28 sec	68.5 kph	Pedestrian falls onto hood, impacts windshield, and is launched
6	48.5 m	3.7 sec	0 kph	Car skids to a stop

Table 1 – Synopsis of sequence of events

Collision speed based on throw distance

Brach & Brach contains several methods for determining collision speed of a vehicle that strikes a pedestrian. A simplistic model is their *hybrid wrap model*:

$$v_{c0} = c_W \cdot \sqrt{s_P}$$

where v_{c0} is the collision speed in m/sec, c_W is a constant with a value of 2.5, 3.6, or 4.5, and s_P is the *throw distance* in m. The distance is $x_6 - x_3$ = 23.85 m. Using the middle value,

$$v_3 = 3.6 \cdot \sqrt{23.85} = 17.6 \text{ m/sec} = 63.3 \text{ kph}$$

Using the higher value as a bracket,

$$v_3 = 4.5 \cdot \sqrt{23.85} = 22.0 \text{ m/sec} = 79.1 \text{ kph}$$

The value predicted above is within this range of speeds.

Since the speed limit on this stretch of road is 100 kph, it can be reasonably concluded that the Ford Kombi was not speeding when it struck the pedestrian.

Movement of pedestrian

The question remains to be answered, could the accident have been avoided? Could the driver of the car have reacted more quickly and avoided the accident?

These questions must address the visibility of darkly-clad pedestrians at night who are moving across the field of vision. Some points:

- Fricke claims that a pedestrian wearing dark clothes cannot be seen at night in less than 53 m.
- From the sequence of events given above, the driver of the car did not see the pedestrian until he was about 25 m away from her.
- In this accident, the pedestrian was not standing in one spot but moving across the roadway, possibly hurrying, to catch the on-coming bus (see Figure 2).
- Fricke also lists the walking speed of a pedestrian as 0.76-1.83 m/sec. If we use a median speed, 1.30 m/sec, then the pedestrian was 1.3 m/sec · 1.24 sec = 1.6 m laterally displaced from the point of impact when the driver first observed her.
- When the Ford was 53 m from the point of impact (when the driver could have noticed the pedestrian directly ahead) there was still 1.79 sec before the impact. At that point, the pedestrian was off to the side 1.3 m/sec · 1.79 sec = 2.3 m.

The lateral displacement of the pedestrian affects the recognition distance. Test were run at the accident scene, and it was determined that a similarly-clad pedestrian could not be seen directly ahead at a distance of more than 30 m (not the 53 m suggested by Fricke). And a pedestrian walking across the field of vision from left to right could not be seen at a distance of more than 20 m.

Using these figures, one can calculate the maximum speed the car could have been traveling to avoid the accident.

Waypoint	Location	Time	Velocity	Acceleration	Description
1	0 m	0 sec		0 m/sec^2	Driver notices pedestrian
2		1.05 sec		-3.92 m/sec^2	Half-braking phase starts
3		1.25 sec		-7.85 m/sec^2	Full-braking phase starts
4	20 m		0 kph	0 m/sec^2	Car comes to a stop

Table 2 – Maximum speed to avoid collision at 20 m

The blank cells indicate unknowns. The initial maximum velocity can be solved via trial-and-error:

1) Assume an initial velocity v_1 .
2) Calculate distance to waypoint 2 with $x_2 = v_1 \cdot t_{12}$.
3) Calculate distance to waypoint 3 with $x_3 = \frac{1}{2} a_{23} \cdot t_{23}^2 + v_2 \cdot t_{23} + x_2$.
4) Calculate velocity at waypoint 3 with $v_3 = \sqrt{2 \cdot a_{23}(x_3 - x_2) + v_2^2}$. $(v_2 = v_1)$

5) Calculate distance to waypoint 4 with $x_4 = -\frac{v_3^2}{2 \cdot a_{34}} + x_3$.
6) If $x_4 \neq 20$ m, go back to step 1 and try a different initial velocity.

This was automated in Excel with the result that v_1 = 39.1 kph to be able to stop within a distance of 20 m. Table 3 summarized the stopping sequence for this case.

Waypoint	Location	Time	Velocity	Acceleration	Description
1	0 m	0 sec	39.1 kph	0 m/sec^2	Driver notices pedestrian
2	11.4 m	1.05 sec	39.1 kph	-3.92 m/sec^2	Half-braking phase starts
3	13.5 m	1.25 sec	36.4 kph	-7.85 m/sec^2	Full-braking phase starts
4	20.0 m	2.54 sec	0 kph	0 m/sec^2	Car comes to a stop

Table 3 – Stopping sequence to avoid collision with pedestrian

The speeds, distances, and times calculated in this study are only approximations, based on average values of drag factors, distances with certain visibilities, etc. A more detailed study would calculate ranges of possible values for these quantities, but the calculation procedures would be the same. Average values were used here to illustrate the analysis procedure without encumbering it with added detail.

Conclusion

The Ford driver did not behave or react carelessly. To avoid the collision with the pedestrian, he would have had to have been driving at 39.1 kph on a stretch of highway where the posted speed limit was 100 kph. The pedestrian apparently did not notice the on-coming Ford because it was dark, because she was hurrying to catch the bus, and because she was distracted, trying to find a flashlight in her purse.

References

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Brach, Raymond and Brach Matthew, Vehicle Accident Analysis and Reconstruction Methods, Second Edition, SAE International, Warrendale, PA, 2011.

Fricke, Lynn B., "Vehicle-Pedestrian Accident Reconstruction", Accident Reconstruction Journal, Waldorf, MD, pages 18-29, January/February 1992.

Car/Pedestrian accident

mu	0.8							
dskid	23.6	m						
g	9.81	m/sec2						
a	7.848	m/sec2						
v3	19.24644	m/sec	69.2872	kph				
apre	3.924	m/sec2						
t2to3	0.2	sec						
v2	20.03124	m/sec	72.11248	kph				
x3-x2	3.927769	m						
treact	1.05	sec						
x2-x1	21.03281	m						
xthick	0.5	m						
dbmpr	0.75	m						
xpedstrk	0.25	m						
x3-x2.5	3.677769	m						
t6-t3	2.452401	sec						
v4	19.29735	m/sec	69.47045	kph				
t4-t2	0.187028							
v5	19.04147	m/sec	68.54929	kph				
t45-t3	0.026118							
Hybrid wrap model:								
3.6	4.883646	17.58113	m/sec	63.29205	kph			
4.5	4.883646	21.97641	m/sec	79.11507	kph			
Walking speeds:		0.76	1.83	1.30				
Lateral position at first sighting:				1.3	1.24	1.612	m	
Time before impact from 53 m:				1.597504	0.19	1.787504		
Lateral position at first sighting:				1.3	1.79	2.327	m	

Maximum initial velocity to stop in 20 m:

v1	10.88889	m/sec	39.2	kph
t12	1.05	sec		
x2	11.43333	m		
a23	-3.924	m/sec^2		
t23	0.2	sec		
x3	13.53263	m		
v3	10.10409	m/sec	36.37472	kph
a34	-7.848	m/sec^2		
x4	20.037	m		
t34	1.29	sec	(from Matlab)	
t4	2.54	sec		