CYCLIST'S CHOICE OF SPEED, RADIUS AND LATERAL ACCELERATION WHILE NEGOTIATING A CURVE: A CLOSED COURSE PILOT STUDY

By Shady Attalla, Richard Robertson and Sam Kodsi

INTRODUCTION

Bicycle collisions account for about 2% of traffic fatalities and 2% of total injuries.[1] One collision scenario between a motor vehicle and a bicycle involves a cyclist travelling along the side of the road, and a vehicle attempting to overtake the slower-moving cyclist. As the car/truck attempts to overtake the bicycle, the cyclist steers to the left (attempting to make a left turn, U-turn, or otherwise), resulting in a collision between the bicycle and the vehicle. Such a scenario accounted for 4.3% of bicycle collisions and 28% of these collisions resulted in serious or fatal injuries.[2]

Within the field of accident reconstruction, the challenge in evaluating this scenario lies in attempting to determine the time it takes the cyclist to perform the leftward movement prior to impact. Maximum and average acceleration and deceleration rates have been studied previously;[3,4,5,6,7,8] however, there is little research on typical acceleration and deceleration rates of cyclists and on recreational cyclists' selection of turning radius, lateral acceleration or lean angle. The purpose of this pilot study was to quantify the "normal" or "everyday" lateral acceleration rates that are used by cyclists in a simulated closed track performance test. Additionally, this study also examined acceleration and deceleration rates (both typical non-emergency and maximum effort) in cyclists varying in age and experience. We intend to expand on the pilot study with data from an open course on public roads and trails.

EXPERIMENTAL TEST SETUP

42 volunteer subjects (14 females and 28 males ranging in age from 10 to 60+ years old) agreed to participate in this study. Data was collected on three separate occasions between 2013 and 2014. All data collection was done in an asphalt parking lot on a dry, level surface. The volunteers were instructed to travel through a closed-course while riding a bicycle. The course was laid out identically for each session. In most cases, the test subjects rode a provided mountain bike style bicycle; however, some of the subjects rode their own bicycle. Each subject was given an opportunity to ride the bicycle and adjust the gear and seat height prior to performing the test.

Each bicycle was instrumented with a GPS data receiver (QStarz 818XT – recording frequency of 10 Hz) to record the speeds, accelerations and position of the bicycle at various points in time. The data from the QStarz 818XT has been compared to data from a Vbox Sport and speeds were found to be within 0.3 m/s between the two instruments. The GPS receiver was linked via Bluetooth to an Android smart phone to log the data, using the RaceChrono app.

The test course was designed to be short in distance and to include relatively tight right and left turns in an attempt to replicate bicycle handling while maneuvering among vehicle traffic, i.e with sudden turns and with stopping and acceleration distances that are too short to reach maximum speeds. For this phase of the study, the test subjects were not expected to reach typical cycling speeds so speed was not an item of study. The course was documented using a survey station to maintain consistency during the three different occasions in which data was gathered.

The test course was divided into two segments. The first segment required the subjects to travel straight for approximately 15 meters, followed by a right turn around 2 pylons. After completing the right turn, the subjects would travel straight for approximately 10 meters, before making a left turn around a single pylon. After completing the left turn, subjects would travel straight for approximately 5 meters, before reaching the starting area for the second segment. Subjects were instructed to stop upon reaching the second segment. Subject volunteers were not given any instruction about how rapidly they should accelerate or how hard they should brake during the first segment of the test course. This was done intentionally so as to capture the typical acceleration and deceleration rates of the subjects during the first segment of the test course. Although lines were drawn on the pavement, the riders were instructed to just use them as a general guide for their intended path and not necessarily for their intended radius.

The second segment involved a straightaway section. In this segment, subjects were instructed to accelerate as quickly as possible, and upon reaching a painted mark in the course (13 meters from their starting position), to brake as quickly as possible in order to come to a complete stop.

Accordingly, the first segment of the course involved subjects travelling at self-selected speeds, acceleration and deceleration rates. The second segment involved maximum longitudinal acceleration and deceleration rates over a short distance.

The provided bicycle was pre-determined and adjusted by the researchers to a middle gear prior to each test subject beginning the testing. During the familiarization time, each test subject had the opportunity to select a different gear. Those subjects riding their own bicycles

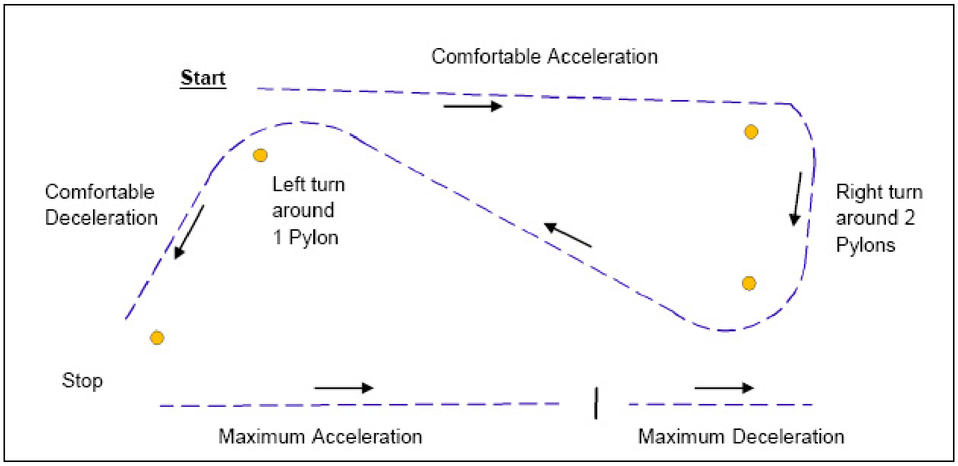

Figure 1. Layout of Test Course

were already familiar with their bicycles and would already have selected a gear. The test subjects were not given any instruction with respect to changing the gears on the bicycle during the test. Most subjects maintained the same gear that they selected during the familiarization and did not adjust the gear setting throughout the duration of the performance test. The figure below illustrates the overall layout of the test course.

RESULTS

During the first segment of the test course, test subjects travelled through the course at a comfortable pace. The results from this first segment are described in Table One.

As discussed above, during the second segment of the course, the test subjects were instructed to accelerate and then brake as hard as they could. The results from the second segment of the testing are described in Table Two.

TABLE 1 - Results from the First Segment of the Test Course

	Average	Standard Deviation
Speed in curve	10.6 km/h 6.5 mph	1.7 km/h 1.1 mph
Natural longitudinal acceleration rate	0.07 g	.02 g
Natural deceleration rate	0.11 g	0.06 g
Natural lateral acceleration rate within turns	0.23 g	0.07 g
Radii travelled within turns	3.9 m 12.8 ft	1.0 m 3.3 ft

TABLE 2 - Results from the Second Segment of the Test Course

	Average	Standard Deviation
Rapid longitudinal acceleration rate	0.13 g	0.03 g
Natural deceleration rate	0.24 g	0.09 g

TABLE 3 - Current Study Compared to Other Research of Natural Longitudinal Acceleration Rate

AASHTO Guidelines	0.05 to 0.1 g (0.5 to 1.0 m/s²)	
Landis et al.	85th percentile 0.05 g (0.5 m/s²)	
Pein	0.06 to 0.08 g (0.57 to 0.8 m/s²)	
Current Study	Mean: 0.07 g	SD: .02 g

COMPARISON TO PREVIOUS RESEARCH

Natural Longitudinal Acceleration Rate

For highway design purposes, the American Association of State Highway and Transportation Officials[9] recommends a bicycle acceleration rate of 0.5 to 1 m/s. This rate is consistant with testing performed by Landis et al and Pein.[5] The new and previous findings are summarized in Table 3.

Natural Deceleration Rate

For calculating traffic signal clearance intervals, AASHTO suggests a bicycle deceleration rate of 0.11 to 0.25 g (1.2 to 2.5 m/s^2) (AASHTO does not specify the research which led to this range). Our testing found average braking rates of 0.11 g ±0.06 g, similar to the lower end of the AASHTO range.

Maximum Deceleration Rate

Mark Crouch[10] presented a mathematical method to calculate the maximum braking possible without the rear wheel of the bicycle lifting. Using typical measurements of a bicycle and rider he found a maximum braking rate of 0.64 g on a surface where a vehicle could brake at 0.7 g.

Other testing was conducted by R. F. Beck[11] and by the New York Statewide Traffic Accident Reconstruction Society.[8] Table 4 lists the results from previous testing and the new test results.

TABLE 4 - Current Study Compared to Other Research of Maximum Deceleration Rate

Landis et al.	Mean: 0.23 g (2.3 m/s², 7.5 ft/s²)	85th Percentile: 0.34 g (3.3 m/s², 10.8 ft/s²)
NYSTARS*	Average: 0.46 g	Range: 0.34 g to 0.56 g
Beck (both brakes)**	Mean: 0.44 g	Range: 0.34 g to 0.52 g SD: 0.15 g
Current Study	Mean: 0.24 g	SD: 0.09 g

* Each test had different parameters (bike type, brake type, rider skill)
** Tests on pavement with auto/road friction factor of 0.73 g, various mountain bike types, brake types and rider skill.

TABLE 5 - Current Study Compared to Other Research of Maximum Acceleration Rate

NYSTARS*	Average: 0.2 g	Range: 0.13 g to 0.31 g
Beck	Mean: 0.13 g	Range: 0.10 g to 0.15 g
Current Study	Mean: 0.13 g	SD: 0.03 g

* Each test had different parameters (bike type, brake type, gear, rider skill)

$$Distance = \frac{\theta}{360} \times 2\pi R$$

Where:

$$\cos\theta = \frac{R - l}{R}$$

or

$$\theta = \cos^{-1}\left(\frac{R - l}{R}\right)$$

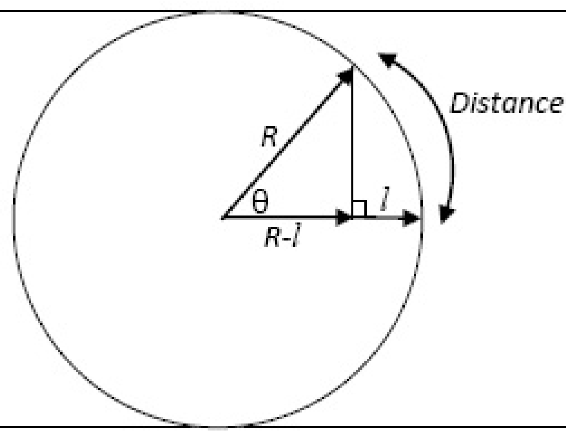

Figure 2. Distance Travelled Around a Circular Arc Relative to lateral Distance

Maximum Acceleration Rate

Table 5 lists the results from previous testing by Beck and by NYSTARS as well as the new test results.

Lateral Acceleration / Turning Radius / Lean

To the best of the authors' knowledge, there have been no studies that directly measured the radius of the curve, the bicycle lean, or the lateral acceleration chosen by cyclists negotiating a curve. In a study by Vansteenkiste et al,[12] subjects were asked to ride a 1.5 m wide circular path at three specified speeds. Their purpose was to study where the riders were looking while negotiating the curve. Their findings of radius ridden at low, medium and high speeds indicated lateral accelerations of 0.08, 0.21 and 0.40 g respectively. The AASHTO guidelines report that casual cyclists are uncomfortable with lean angles greater than 15° to 20° (AASHTO does not specify the research which led to this range). The results from the current study indicate an average speed of 10.6 km/h within the curves. The AASHTO guidelines suggest a cyclist travelling at this speed would comfortably maneuver a turn with a minimum radius of 2.4 to 3.3 m which was towards the lower end of the range in the current study. Most of the test subjects tended to ride a turn with a larger radius than suggested by AASHTO at an average speed of 10.6 km/h. The AASHTO range of comfortable lean (15° to 20°) equates to a lateral acceleration of 0.27 to 0.36 g. Most of the subjects in the current study chose to ride through the curves with a lateral acceleration (0.17 to 0.3 g) corresponding to a lean angle between 10° and 17°.

DISCUSSION

The results of this study expand on previous research regarding longitudinal bicycle acceleration and deceleration. The results would be most suitable for situations of tight maneuvering, accelerations over short distances and braking from slower speeds. Since this course was designed to be short in distance, the rapid acceleration and emergency deceleration findings should not be relied upon as representing the maximum in most situations. This testing added new data concerning cyclists negotiating curves – their speed, radius and lateral acceleration.

Drivers of 4 wheeled motor vehicles tend to not exceed a comfortable level of lateral acceleration in everyday driving. In the case of single-track vehicles such as bicycles or motorcycles, the comfort level comes from the lean angle needed so that the bicycle or motorcycle remains upright. The formula used for lean angle is

$$\tan \varphi = V^2 / R\,g$$

This formula is derived from the lateral (centrifugal) acceleration,

$$a_{lateral} = V^2 / R$$

in units of m/s^2 or ft/s^2, being counter-acted by leaning the bicycle or motorcycle.

Given the bicycle speed, we can use the results of this study to determine an estimated turning radius that a cyclist would likely choose. Similarly, if the incident scene dictates the radius of the cyclist's path, we can determine the speed at which a typical cyclist would negotiate the curve. There is a limiting factor of a maximum lean angle which would allow the pedals of the bicycle to strike the pavement.

Consider a hypothetical scenario in which a vehicle is passing with its right side 2 m from a bicycle. The bicycle is travelling at a constant speed of 20 km/h (5.6 m/s) [12.4 mph, 18.4 ft/s] when the rider decides to turn left. Based on our findings in the current study, this research yielded a range of lateral accelerations of 0.17 to 0.3 g (where g = 9.81 m/s^2 [32.2 ft/s^2]).

$a_{lateral} = V^2 / R$ Formula for lateral acceleration

$R = V^2 / a_{lateral}$ Rearranged to solve for R

$R = \frac{5.6^2}{0.3 \cdot 9.81}$ to $\frac{5.6^2}{0.17 \cdot 9.81}$ Substituting our metric values (V = 5.6 m/s, a = 0.17 to 0.3 g)

R = 10.7 to 18.8 m

$R = \frac{18.4^2}{0.3 \cdot 32.2}$ to $\frac{18.4^2}{0.17 \cdot 32.2}$ Substituting our imperial values (V = 18.4 ft/s, a = 0.17 to 0.3 g)

R = 34.9 to 61.8 ft

Substituting in our values, we find that the bicycle would most likely turn to the left at a radius of 10.7 to 18.8 m. To move a lateral distance of 2 m to reach the side of the passing vehicle, the bicycle would travel around its circular path a distance of 6.6 to 8.8 m. (This distance can be obtained with a geometric construction in CAD or calculated as derived in Figure 2.) At 5.6 m/s, the bicycle would reach the right side of the vehicle in 1.2 to 1.6 seconds.

CONCLUSIONS

The purpose of this pilot study was to provide a course requiring the test subjects to negotiate curves of different sizes to determine the combination of speed and radius (and therefore lateral acceleration) selected by the subjects. In the current study, most cyclists were found to negotiate the turns with a lateral acceleration between 0.17 and 0.3 g. These findings can be used in accident reconstruction to help predict the likely turning path of typical cyclists or the speed at which they would turn.

The longitudinal accelerations and decelerations found in the current study were toward the low end of previous closed-course studies and design guidelines. The test subjects in this study may have been cautious due to the artificial nature of the course, not cycling on a routine basis and the fact that many were riding an unfamiliar bicycle. A future study should be performed on real-world roadways and trails. Test subjects should be habitual riders on their own bicycles and categorized by riding experience and bicycle type. Such a study would refine the findings of the current study and confirm their appropriateness for real-world situations.

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