Overview

1. Road Evidence
   - Spin examples
   - Critical Speed Yaws
   - Turning and Braking
2. Definitions
3. Critical Speed Formula
4. Drag Factors and Skid Testing
5. Lane Changes
Overview

6. Testing and Instrumentation
7. Dynamic Roadway Marking System
8. Data Analysis and Reduction
9. Validation of Lane Change Equation
10. Derivation of Critical Speed Yaw Formulation
11. Summary and Questions

Road Evidence

- Maximum performance lateral maneuvers will saturate one or more of the tires of the vehicle.
- Because lateral motion happens concurrently with forward motion, any saturated tires will leave curving marks on the road.
Road Evidence

- Our ability to interpret these curving tire marks will allow us to choose a proper method for speed analysis.
- We will examine several different types of curving tire mark evidence in the following slides.

Road Evidence - Spins

- A spin is a vehicle motion characterized by relatively high angular velocities.
- A vehicle may spin as a result of inappropriate steering, especially on low coefficient surfaces.
- A vehicle may also enter a spin as the consequence of a collision.
- Uneven braking may also result in a spin.
Emergency Brake Spin

- If the emergency brake only is used, the vehicle will tend to spin around.
- A combined speed technique may be used to analyze speed.
- The vehicle will track straight for a distance and will then rotate.
- The straight portion may be calculated with a straightforward speed equation, while the spin portion may be calculated with the spin analysis.

Road Evidence - Spins

- This is a steering induced spin.
- A spin analysis, such as was presented in Special Problems 2003, would be appropriate for speed analysis.
Road Evidence - Spins

- These tire marks show a steering induced spin resulting from the driver’s inappropriate response in coming back onto the road.
- A spin analysis would be appropriate for speed analysis.

Speed at Separation: 45 mph
Heading Change: 206 deg
Center of mass distance: 94.5 ft
Scale: 1" = 15'
RF wheel disabled
Test #5
Road Evidence - Spins

- Angular velocity for spins are typically on the order of 100 degrees per second or higher.
Road Evidence – Critical Speed

Yaw - Definitions

• Yaw refers to the orientation of the vehicle.
• Specifically, the heading of the vehicle is not co-linear with the velocity vector of the vehicle.
• The evidence showing this are the tire scuffs on the road.
• The rear tires track outside the corresponding front tires.

Definitions, cont’d.

• “Critical” refers to the idea that we may identify the lateral acceleration as the maximum tire friction on the road.
• We obtain this friction information with a test skid.
• We may have to correct our test skid information for grade or superelevation.
• The ONLY way a vehicle gets onto a critical speed yaw is through the application of an inappropriate steering input (over correction or acceleration)!
Road Evidence – Critical Speed Yaw

In order to properly analyze a critical speed yaw situation, we must recognize the tire mark evidence left behind. Note the diagonal striations and uneven edge of the tire marks left in the following photos.

The rear tires begin tracking outside the front tires.
Critical Speed Yaw Marks

- A yaw results when the velocity vector and heading of the vehicle are not co-linear.
- If the yaw is the result of inappropriate steering input, then the yaw may be a "Critical Speed Yaw", and may be used for speed analysis in a simple, straightforward manner.
- This photo illustrates a critical speed yaw. Notice the rear tires track outside the corresponding front tires.

Critical Speed Yaw Marks

- This crash began with critical speed yaw marks on the shoulder.
- We can use shoulder drag to get a conservative speed estimate.
- We may average shoulder and road drag to get an upper limit speed.
Critical Speed Yaw Marks

- This is a CSY mark left with no braking.
- Note the direction of the striations in the tire mark.

Braking and Turning Marks

- This is a CSY mark left with ABS braking.
- Note the direction of the striations in the tire mark.
- As the brake force increases, the angle of the striations approaches parallel.
Braking and Turning

- This is a CSY mark left with ABS braking.
- Note the direction of the striations in the tire mark change as the ABS system cycles.
- The average lateral acceleration is a little below the average ABS drag factor.

Braking and Turning

- Transition from CSY to full, non-ABS braking.
- This evidence may be left by the panicked, untrained driver who inappropriately steers and then brakes to maximum.
- The yaw portion follows the CSY model.
Braking and Turning

• Controlled braking and turning by a trained driver. Rear ABS only.
• The inside mark is a skid, with longitudinal striations.
• The rear tires track outside the corresponding front tires.
• The outside tire marks show diagonal striations.
• May NOT use the CSY analysis with a full drag factor.
• Lateral acceleration is significantly lower than the full drag factor.
• Evidence does NOT support the CSY analysis. A skid analysis would be more appropriate.
Braking and Turning

Curving Acceleration Scuff

- This is a curving tire mark, but does not indicate a yaw.
- This is a curving acceleration scuff.
- It may not be analyzed for speed with a CSY analysis.
Speed Determination with CSY

- The equation for determining speed from CSY is based upon the concepts of Uniform Circular Motion.
- We make the assumption the vehicle will actually move in a decreasing spiral, because the vehicle is slowing as it progresses through the yaw.
- We may further assume the vehicle trajectory may be approximated as a series of circular arcs.
- These arcs will progressively decrease in radius.

Critical Speed Yaw of 2003 Chevy Malibu (VC3000 Computer)

Initial value as calculated: 0.26
Speed Determination with CSY

- We may also assume the lateral acceleration factor may be determined through skid testing.
- Finally, we must show the vehicle is in equilibrium. In other words, the vehicle is in a steady state cornering condition.
- If this steady state condition is met, then the lateral acceleration stays at a constant level for some time.
- All of these concepts will be more fully explored by the presentation tomorrow...

Speed Determination with CSY

- The same concepts we use to analyze speed from a CSY analysis have been historically used by Highway Engineers to design roads.
- In the 1965 "Blue Book" (AASHO), pg 152, we may find the following equation:
Critical Speed Yaw Derivation

- Recall the definition of Vectors:
  - Quantity that possesses both MAGNITUDE and DIRECTION.

- Recall the definition of Velocity:
  - A change in DISPLACEMENT with respect to a change in TIME.

- Recall the definition of Acceleration:
  - A change in VELOCITY with respect to a change in TIME.
Critical Speed Yaw Derivation (cont.)

- Velocity and Acceleration are vector quantities.
- Thus, if the MAGNITUDE of a moving vehicle’s velocity changes, there is an Acceleration.
- And if the DIRECTION of a moving vehicle changes, there is an Acceleration (because the velocity is changed).

Therefore a vehicle traveling at constant velocity (magnitude) in a curve is undergoing an Acceleration (since it’s continually changing directions).

More specifically, it is experiencing a Lateral Acceleration.
For a vehicle to move laterally left or right, it requires surface friction.

More specifically, it requires a force which the surface friction will produce in the lateral direction (i.e. perpendicular to the longitudinal velocity vector).

If the surface friction is greater than the lateral friction the vehicle is needing to travel in a curving path, the vehicle will be able to successfully negotiate the curving path.

If the vehicle requires more lateral friction than the surface can provide, then the vehicle will begin to lose control.

A vehicle traveling in a curving path is experiencing both lateral and longitudinal forces.

Let’s look at the lateral forces the vehicle is experiencing.
Critical Speed Yaw Derivation (cont.)

Let’s first look at lateral forces for a vehicle traveling in a curved path, at constant speed on a flat surface.

- Some of these forces will be normal (perpendicular) to the surface.
- The rest will be parallel to the surface.
Critical Speed Yaw Derivation (cont.)

- First, forces normal to the road surface:

\[ W \quad F_n \]

Critical Speed Yaw Derivation (cont.)

- Now, let’s look at the forces parallel to the roadway.

- These forces will be lateral to the vehicle.

- Some are due to the dynamics of the vehicle in the curve and some will be due to the surface friction.
Critical Speed Yaw Derivation (cont.)

- Forces parallel to the road surface:

\[ F_f \quad W \quad F_n \]

Displaying both normal and lateral forces on the same diagram looks like this:
Let's examine the lateral forces on the vehicle corning on a banked road.

As before, there will be forces normal to the road and parallel to the road.

But we now have to take the bank, or angle of the road into account.

---

Forces in the vertical direction:

\[
\begin{align*}
W & \uparrow \\
F_n & \uparrow \\
Ma & \uparrow \\
W \cos \theta & \uparrow \\
W \sin \theta & \uparrow
\end{align*}
\]
Critical Speed Yaw Derivation (cont.)

- Forces in the lateral direction:

\[
F_f = M_a \cos 2 \quad W \sin 2
\]

Displaying both normal and lateral forces on the same diagram looks like this:
Critical Speed Yaw Derivation (cont.)

- Let’s look at equations which describe the previous slides.

Forces normal to the road surface

Since the vehicle is neither moving up off the road surface or down into the road surface, the vehicle is in equilibrium. In other words the force vectors balance.

Mathematically:

\[ \sum F_n = 0 \]

Critical Speed Yaw Derivation (cont.)

Substituting in the vectors:

1) \[ F_n - w \cos \theta - Ma \sin \theta = 0 \]

Rearrange:

\[ -w \cos \theta - Ma \sin \theta = -F_n \]

Multiply through by -1:

2) \[ w \cos \theta + Ma \sin \theta = F_n \]
Critical Speed Yaw Derivation (cont.)

Forces parallel to the road surface

Since the vehicle is not sliding up or down the superelevation, the vehicle is in equilibrium. In other words the force vectors balance.

Mathematically:

\[ \sum {F_t} = 0 \]

Substituting in the vectors:

3) \( F_f + w \sin \theta - Ma \cos \theta = 0 \)

Rearrange:

4) \( F_f + w \sin \theta = Ma \cos \theta \)

Recall:

5) \( F_f = \mu F_n \)

Substitute Eq. 2 into Eq. 5:

6) \( F_f = \mu (w \cos \theta + Ma \sin \theta) \)
Critical Speed Yaw Derivation (cont.)

Substitute Eq. 6 into Eq. 4:

7) \( \mu (w \cos \theta + Ma \sin \theta) + w \sin \theta = Ma \cos \theta \)

Expand the left side:

8) \( w \mu \cos \theta + Ma \mu \sin \theta + w \sin \theta = Ma \cos \theta \)

Newton’s Second Law tells us that lateral acceleration is: \( a = \frac{v^2}{r} \)

And we know: \( M = \frac{w}{g} \)

Multiply both sides by \( \frac{1}{w} \) and group terms:

9) \( \frac{w}{g} \mu \cos \theta + \frac{w}{g} \mu \sin \theta + w \sin \theta = \frac{w}{g} \frac{v^2}{r} \cos \theta \)

Divide both sides by \( \cos 2 \):

10) \( \mu \cos \theta + \frac{v^2}{gr} \mu \sin \theta + \sin \theta = \frac{v^2}{gr} \cos \theta \)

11) \( \mu + \frac{v^2}{gr} \mu \frac{\sin \theta}{\cos \theta} + \frac{\sin \theta}{\cos \theta} = \frac{v^2}{gr} \)
Critical Speed Yaw Derivation (cont.)

Recall \( \frac{\sin \theta}{\cos \theta} = \tan \theta \) substitute it into Eq. 11

\[ 12) \quad \mu + \frac{v^2}{gr} \mu \tan \theta + \tan \theta = \frac{v^2}{gr} \]

Recall that \( \tan 2\theta = \text{slope} = e \). Substitute \( e \) for \( \tan 2\theta \):

\[ 13) \quad \mu + \frac{v^2}{gr} \mu e + e = \frac{v^2}{gr} \]

Critical Speed Yaw Derivation (cont.)

Subtract the center term on the left side from both sides:

\[ 14) \quad \mu + e = \frac{v^2}{gr} - \frac{v^2 \mu e}{gr} \]

Group the right side terms over the common denominator \( gr \):

\[ 15) \quad \mu + e = \frac{v^2 - v^2 \mu e}{gr} \]
Critical Speed Yaw Derivation (cont.)

Multiply both sides by $gr$:

16) $gr(\mu + e) = v^2 - v^2 \mu e$

Factor $v^2$ out of the right side elements:

17) $gr(\mu + e) = v^2(1 - \mu e)$

Divide through by $(1 - \mu e)$:

18) $\frac{gr(\mu + e)}{1 - \mu e} = v^2$

Take the square root and rearrange:

19) $v = \sqrt{\frac{gr(\mu + e)}{\sqrt{1 - \mu e}}}$

Bring $g$ out:

20) $v = \sqrt{g} \frac{\sqrt{r(\mu + e)}}{\sqrt{1 - \mu e}}$
Critical Speed Yaw Derivation (cont.)

Substitute 32.2 for \( g \) and take the square root of 32.2:

\[
\nu = \frac{5.67 \sqrt{r(\mu + e)}}{\sqrt{1 - \mu e}}
\]

Substitute 1.466 \( S \) for \( \nu \):

\[
1.466 S = \frac{5.67 \sqrt{r(\mu + e)}}{\sqrt{1 - \mu e}}
\]

Divide through by 1.466 and substitute \( f \) for \( \nu \):

\[
S = \frac{3.86 \sqrt{rf}}{\sqrt{1 - \mu e}} \quad \text{Equation for Critical Speed on a Curve with Positive Superelevation}
\]

If \( e = 0 \), then:

\[
S = 3.86 \sqrt{rf} \quad \text{Equation for Critical Speed on a Level Curve}
\]

Performing the same type of analysis for a negative superelevation will yield:

\[
S = \frac{3.86 \sqrt{rf}}{\sqrt{1 + \mu e}}
\]
Skid Testing

- In order to get the proper drag factor for a critical speed calculation, we must do test skids.
- Results between tests must be consistent.
- The following tests were conducted at the Wisconsin State Patrol Academy in August 2002.
Close-up of Sliding Contact Patch

Spackling indicates the tire is braking at or near maximum.
Deceleration Factor Tests for 1997 Ford Crown Victoria with ABS Disabled

Rear Brakes did not lock up

Deceleration Factor Tests from VC2000 Accelerometer for 2002 Pontiac Grand Prix

All Pontiac ABS Tests
Acceleration Factor Tests
from VC2000 Accelerometer

All Test Skids

Measuring Grade
Measuring Super-elevation

Radius Determination

- For the steady-state CSY, once we have chord and middle ordinate measurements, we may calculate the radius of the outside front tire mark with the following equation:

\[ R = \frac{c^2}{8m} + \frac{m}{2} \]

- To get the CM radius, subtract \( \frac{1}{2} \) of the track width from this calculation.
Lane Changes

- The purpose of this research is to determine the dynamic response of three types of vehicles in high performance lane change maneuvers.
- A lane change maneuver requires the vehicle to move laterally into a parallel path in the width of a highway lane, typically 12 feet or so.
- In a high performance maneuver, the steering input will be completed quickly, first one direction, then the other.

Lane Changes

- Because these maneuvers take place in little distance and time, they are transient in nature.
- As such, the vehicle does not have time to reach an equilibrium, or steady state condition, before the vehicle is asked by the driver to change direction again.
- These high performance lane changes may cause tire(s) to saturate and mark the road.
Lane Changes

- To a neophyte investigator, these tire marks may sometimes be mistaken for CSY marks.
- Because of the transient nature of the vehicle motion, we may not use a classical CSY analysis to compute speed from these marks.
- We will design testing to examine important aspects of vehicle motion during lane change maneuvers.
- We will also examine the potential error of using a CSY analysis for speed, and will examine the sources of the error.

Lane Changes

- Simple models exist to generally examine lane change maneuvers if the entrance speed and lateral acceleration are specified. (FTAR Chapter 7)
- These models were initially developed to examine lane changes with lateral accelerations encountered in normal driving.
- The distance equation of the analysis was essentially validated in SAE 2002-01-0817 (Araszewski, et al).
- The average error for 15 tests was 0%.
Lane Changes

• Our testing will examine this simple model to see if we may get reasonable results for distance and angle for these high performance maneuvers.
• Finally, we will see if we can develop a simple method to determine speed from the characteristics of lane change tire marks.
Lane Changes

Lane Changes
Test Design

- In order to describe the vehicle motion, we will want to measure the following data points:
  - Lateral Acceleration, Gs
  - Longitudinal Acceleration, Gs
  - Yaw Rate, degrees per second
  - Steer Angle
  - Time based position on the road

Instrumentation

- The VC-3000 is a turn-key system for our research.
- This accelerometer system may be configured with yaw rate sensors mounted remotely.
- We set this system up with the unit mounted on the windshield and the yaw rate sensors mounted on the dash.
- We used a string potentiometer mounted on the steering rack to determine steering wheel angles. (Jacksonville Tests)
Instrumentation

Dynamic Roadway Marking System (DRMS)™ Patent Pending

- History
  - Seed from using two shot markers as SP2003 for spin analysis
  - Needed distance and orientation data
- Solution: DERMS
  - Modern electronic paint ball markers provide repeating fire
  - Remote control and diagnostic
Dynamic Roadway Marking System (DRMS)™ Patent Pending

- **History**
  - Seed from using two shot markers as SP2003 for spin analysis
  - Needed distance and orientation data

- **Solution: DERMS**
  - Modern electronic paint ball markers provide repeating fire
  - Remote control and diagnostic box
DRMS Mounted to the Receiver on a Dodge Dakota

DRMS Mounted to the License Plate Bracket of the Dakota
DRMS Mounted on the Back of a Ford Crown Victoria

Dodge Dakota (Ohio Testing)
Interpreting DRMS markings

- Total Station Mapping of the Points
- Import to CAD
- Method #1:
  - Draw lines connecting front the dot to rear dot
  - Record location of midpoint and orientation
  - Determine COM
- Method #2:
  - Measure the car to make a CAD symbol with the DRMS included.
  - Place the symbol over the paintball marks

DRMS Specifications

- Maximum Frequency is 8-9 shots per second.
- Frequency is adjustable.
- Duration of fire is adjustable from 1 second to 30 seconds.
- Time lag from fire pulse to paint mark is 50 ms (height dependent).
- 12 V power input.
DRMS Features

- Remote firing of markers.
- Communicates with the VC3000.
- Provides a physical link between roadway evidence and instrument data
- Usable on any vehicle
  - Mounts to a license plate bracket
  - Mounts to a hitch receiver
  - Drill new mounting points
- Consistent time base between shots

Information Provided by DRMS

- Time when markers are fired
- If one marker:
  - Location of one point of car
  - Orientation and Center of Mass location if there are tire marks
- If two markers:
  - Location and orientation regardless of tire evidence
- Speed and acceleration can be backed out
Application of the DRMS

- Vehicle Testing and Reconstruction
  - Validation of formulas
    - Critical Speed Yaw
    - Lane Change
  - Spin Analysis and Research
  - Perception-Reaction Distance
  - Commercial Vehicle Amplification Ratios
- Teaching Aides
  - Illustrate acceleration (ticker tape)
  - Evidence interpretation
- Vehicle System Identification

Real Data from Paint Marks

- Extract X and Y coordinates of the midpoint of the line from the CAD drawing
- Determine the angle of the line

Approach Velocity = 45 mph
Rotate Coordinate Systems

- Put the approach on the X axis
  
  \[ x' = x \cos \theta + y \sin \theta \]
  \[ y' = x \sin \theta - y \cos \theta \]

- The angle is the Approach Angle

Adjust for Center of Mass

- Translate the Coordinate system to make the initial point of interest the origin
- Adjust for the COM based on the distance from the midpoint, \( r \)
  - Make sure to include the angle components

\[ COM_x = x + r \cos \theta \]
\[ COM_y = y + r \sin \theta \]
Typical Results of Lane Change Maneuver - Crown Victoria

- Known Entrance Speed
  - VC 3000 and ODBII
  - 42.52 mph
- Radius from 30 ft Chord
  - 222.59 ft
- Speed from CSY
  - 52.14 mph
- 22% error

Lane Change Path from DRMS

Time History of Vehicle Performance based on VC3000 Data
Why is There Error?

- Assume a constant lateral acceleration
  - Lateral acceleration is present for only 54 ft based on shot marks
  - ½ second duration
- Assume Constant Radius
  - Radius actually increases
  - Behaves like a spiral
  - CSY analysis would yield 143 ft @ 42 mph and $f = 0.82$
Relative Radii

Radius Based on Actual Speed

Radius from Chord & M.O.

Radius Problems

Path of the Center of Mass for a Lane Change

Uniform Circular Arc, Radius = 143
Lane Change Maneuver for a Dodge Dakota

- Known Entrance Speed
  - VC 3000
  - 43.34 mph
- Radius from 30 ft Chord
  - 232.54 ft
- Speed from CSY
  - 51.98 mph
- 19.9% error

Lane Change Path from DRMS

Lane Change Example of a Pickup

Time History of Vehicle Performance based on VC3000 Data
Lane Change Example of the Achieva

Time History of Vehicle Performance based on VC3000 Data

-1 -0.8 -0.6 -0.4 -0.2 0 0.2 0.4 0.6 0.8

Acceleration

-25 -20 -15 -10 -5 0 5 10 15 20

Rate Gyro (degrees/sec)

-25 -20 -15 -10 -5 0 5 10 15 20

Accel (G)

Lat Accel (G)

Rate Gyro (degrees/sec)

Validation of Lane Change Equations

- Speed is measured
- Drag Factor is reduced by 80%
- From survey data we can find m and d

\[
\begin{align*}
S & = \text{Speed} \\
R & = \frac{S^2}{14.89f} \\
\theta & = \sin^{-1}\left(\frac{d}{R}\right)
\end{align*}
\]

\[
d = 0.366S\sqrt{\frac{m}{f}}
\]

Validation of Lane Change Equations

- Predicted angle agrees with measured angle within 2 degrees
- Distance agrees within 2 feet
- Computes an “Effective Radius”
- Working backward to obtain speed is too sensitive to the small angle.
- 2 degrees can give 10 mph differences.

Speed From Lane Change

- Work in this area is preliminary, but shows promise.
- We wish to develop techniques that will allow the scene investigator to take evidence measurements that may be converted into a path radius that is both accurate and repeatable.
- We must also account for the shape of the lateral acceleration curve.
Speed From Lane Change

Work with the Olds tests in Jacksonville have resulted in a speed calculation within one mph of the integrated entry speed.

More analysis and more tests need to be done, but the method shows promise and will be published when finished.

Summary and Conclusions

- CSY Analysis is inappropriate for determining speed from a transient lane change maneuver.
- Interpretation of the evidence is paramount to recognizing the lane change.
- Testing was conducted using the VC3000DAQ Accelerometer and the Dynamic Roadway Marking System™
- Test show errors for lane changes
- Lane Change equations presented in FTAR are validated.