Fundamentals of Vehicle Dynamics

Thomas D. Gillespie

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PREFACE

Throughout all of history it is doubtful that any invention has so effectively captured the interest and devotion of man as the automobile. The mobility enjoyed by humanity in the twentieth century has become an integral component of the modern lifestyle. In this first century of its history, more than a billion automobiles have been manufactured to satisfy the appetite for personal mobility. The marvels of mass production at times have reduced the cost of an automobile to only a few months of personal income. Most profoundly, however, for many people automobiles are a first love at some point in their lives, taking first priority with their interest and finances. In the words from a poem penned in earlier days:

I drive my “Lizzie” every day,
   Up hill, down dale, and every way.
A faithful auto it has been
   Even if it is of tin.

I’ll have to say — It’s rattling good.
   — The engine, it’s beneath the hood,
   — The wheels turn backward in reverse,
   — The paint it’s looking worse and worse.

When I have money in my jeans,
   I’ll not ride in a can of beans,
I’ll buy what’s called an “automobile.”
   Won’t I look fine behind the wheel.

— T. N. Gillespie

Much of the infatuation with the automobile has centered around performance—acceleration, braking, cornering and ride. The art is practiced by the backyard mechanic, the racing enthusiast, and the automotive engineer. A library of books, magazine articles, and technical papers has been written to explain the engineering principles, the rules of thumb, and sometimes the “wrong way” to enhance the performance of an automobile. Most of the books written by practitioners from the racing circuits expound the wisdom of experience but without rigorous engineering explanation. A few textbooks have been written by those knowledgeable in automotive engineering, but the
books are often rather analytical and theoretical in nature. This book attempts to find the middle ground—to provide a foundation of engineering principles and analytical methods to explain the performance of an automotive vehicle, when those explanations are not too laborious, and to smooth the way between the doses of equations with practical explanations of the mechanics involved. The inclusion of engineering principles and equations biases the book to interest only the engineer, but it is hoped that the explanations are complete enough that those without a formal engineering degree can still comprehend and use most of the principles discussed.

Those responsible for the design and development in the manufacturing companies today are challenged by questions about the qualities desired in the product by the customer, and how these qualities are related to design and manufacturing processes. In recent years the complexity of the automotive design process has been increased by regulatory actions arising from the social and environmental consequences of the millions of motor vehicles operating on our highways. Added to this is the competitive pressure of the modern automotive manufacturing industry. In order to remain competitive in the future the manufacturers must seek ways to improve the efficiency of the design and development processes and shorten the time span from concept to production. Achievement of these goals requires a better understanding of the automobile as a system, so that qualities and performance of proposed designs can be predicted at an early stage in the design evolution, allowing refinements to be introduced while there is minimal impact to program costs.

Acceleration, braking, turning and ride are among the most fundamental properties of a motor vehicle and, therefore, should be well understood by every automotive engineer. Performance in one mode is closely linked to the others as a consequence of the dependence on a common set of vehicle mechanical properties. To understand the vehicle as a system it is necessary to acquire a knowledge of all the modes. Motion is the common denominator of all these modes; thus, the study of this field is denoted as vehicle dynamics.

The objectives in writing this book were:

1) To introduce the basic mechanics governing vehicle dynamic performance in the longitudinal (acceleration and braking modes), ride (vertical and pitch motions), and handling (lateral, yaw, and roll modes). Engineering analysis techniques will be applied to basic systems and subsystems to derive the controlling equations. The equations reveal which vehicle properties are influential to a given mode of performance and provide a tool for its prediction. By understanding the derivation of the equations, the practitioner
is made aware of the range of validity and limitations of the results.

2) *Familiarization with analytical methods available.* Over past decades analytical methods have been developed for predicting many aspects of automotive performance. Although the engineer has no need to master and utilize these techniques in daily activity, a knowledge of their existence greatly increases his/her value to the company. Awareness of these methods is the first step in knowing what is possible and where to find the necessary tools when the need arises.

3) *Familiarization with terminology.* Clarity in communication is vital to problem solving. Over the years, appropriate terminology for automotive engineering has been defined to facilitate communication. The study of vehicle dynamics provides the opportunity to become familiar with the terminology.

Thomas D. Gillespie
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This book is dedicated to my wife, Susan, and our four wonderful children, Dave, Darren, Devin and Jessica. Throughout the long hours necessary to prepare these materials they have shown me patience and encouragement—two ingredients essential to any such endeavor.

The author is also indebted to many colleagues in the vehicle dynamics community who have provided comments and encouragement in preparation of this manuscript. Among those who have contributed their time and energy are Paul Fancher, Sam Clark, Charles MacAdam, Ray Murphy, James Bernard, Bill Fogarty, Manfred Rumple, Bill Stewart, Chuck Houser, Don Tandy, and the many dedicated staff members of the Society of Automotive Engineers.
LIST OF SYMBOLS

\( a \)  Tire cornering stiffness parameter
\( b \)  Tire cornering stiffness parameter
\( A \)  Frontal area of a vehicle
\( A_f \)  Lateral force compliance steer coefficient on the front axle
\( A_r \)  Lateral force compliance steer coefficient on the rear axle
\( a_X \)  Acceleration in the x-direction
\( a_Y \)  Acceleration in the lateral direction
\( b \)  Longitudinal distance from front axle to center of gravity
\( c \)  Longitudinal distance from center of gravity to rear axle
\( C_\alpha \)  Cornering stiffness of the tires on an axle
\( C_\alpha' \)  Cornering stiffness of one tire
\( C_{\alpha} \)  Tire cornering coefficient
\( C_\gamma \)  Tire camber stiffness
\( C_D \)  Aerodynamic drag coefficient
\( C_H \)  Road surface rolling resistance coefficient
\( C_L \)  Aerodynamic lift coefficient
\( C_{PM} \)  Aerodynamic pitching moment coefficient
\( C_{RM} \)  Aerodynamic rolling moment coefficient
\( C_{YM} \)  Aerodynamic yawing moment coefficient
\( C_S \)  Suspension damping coefficient
\( C_S \)  Aerodynamic side force coefficient
\( C_P \)  Center of pressure location of aerodynamic side force
\( d \)  Lateral distance between steering axis and center of tire contact at the ground
\( d_h \)  Distance from axle to the hitch point
\( d_{NS} \)  Distance from center of mass to the neutral steer point
\( D \)  Tire diameter
\( D_I \)  Dynamic index
\( D_X \)  Linear deceleration
\( D_A \)  Aerodynamic drag force
\( e \)  Height of the pivot for an “equivalent torque arm”
\( \Delta \)  Drum brake geometry factor
\( E[y^2] \)  Mean square vibration response
\( f \)  Longitudinal length for an “equivalent torque arm”
\( f_a \)  Wheel hop resonant frequency (vertical)
Undamped natural frequency of a suspension system (Hz)
Rolling resistance coefficient
Braking force
Vertical disturbance force on the sprung mass
Imbalance force in a tire
Force in the x-direction (tractive force)
Maximum brake force on an axle
Total force in the x-direction
Force in the y-direction (lateral force)
Lateral force on an axle
Lateral force on one tire
Force in the z-direction (vertical force)
Vertical force on inside tire in a turn
Vertical force on outside tire in a turn
Tire/wheel nonuniformity force on the unsprung mass
Acceleration of gravity (32.2 ft/sec$^2$, 9.81 m/sec$^2$)
Brake gain
Road roughness magnitude parameter
Power spectral density amplitude of road roughness
Power spectral density amplitude of sprung mass acceleration
Center of gravity height
Height of the aerodynamic drag force
Hitch height
Height of the sprung mass center of gravity above the roll axis
Height of suspension roll center
Tire section height
Engine or brake horsepower
Aerodynamic horsepower
Rolling resistance horsepower
Road load horsepower
Response gain function
Moment of inertia of the driveshaft
Moment of inertia of the engine
Moment of inertia of the transmission
Moment of inertia of the wheels
Moment of inertia about the x-axis
### List of Symbols

- \( I_{yy} \): Moment of inertia about the y-axis
- \( I_{zz} \): Moment of inertia about the z-axis
- \( k \): Radius of gyration
- \( K \): Understeer gradient
- \( K_{at} \): Understeer gradient due to aligning torque
- \( K_{llt} \): Understeer gradient due to lateral load transfer on the axles
- \( K_{lfCS} \): Understeer gradient due to lateral force compliance steer
- \( K_s \): Vertical stiffness of a suspension
- \( K_{ss} \): Steering system stiffness
- \( K_{strg} \): Understeer gradient due to the steering system
- \( K_t \): Vertical stiffness of a tire
- \( K_\phi \): Suspension roll stiffness
- \( L \): Wheelbase
- \( L_A \): Aerodynamic lift force
- \( m \): Drum brake geometry parameter
- \( M \): Mass of the vehicle
- \( M_{AT} \): Moment around the steer axis due to tire aligning torques
- \( M_L \): Moment around the steer axis due to tire lateral forces
- \( M_r \): Equivalent mass of the rotating components
- \( M_{SA} \): Moment around the steer axis due to front-wheel-drive forces and torques
- \( M_T \): Moment around the steer axis due to tire tractive forces
- \( M_V \): Moment around the steer axis due to tire vertical forces
- \( M_\phi \): Rolling moment
- \( n \): Drum brake geometry parameter
- \( N \): Normal force
- \( N_t \): Numerical ratio of the transmission
- \( N_f \): Numerical ratio of the final drive
- \( N_{tf} \): Numerical ratio of the combined transmission and final drive
- \( NSP \): Neutral steer point
- \( p \): Pneumatic trail
- \( P_a \): Brake application pressure/effort
- \( P_{atm} \): Atmospheric pressure
- \( P_f \): Front brake application pressure
- \( P_r \): Rear brake application pressure
- \( P_s \): Static pressure
- \( P_t \): Total pressure
PM  Aerodynamic pitching moment
p  Roll velocity about the x-axis of the vehicle
q  Pitch velocity about the y-axis of the vehicle
q  Dynamic pressure
r  Yaw velocity about the z-axis of the vehicle
r  Rolling radius of the tires
rk  Ratio of tire to suspension stiffness
R  Radius of turn
Rh  Hitch force
Rg  Grade force
Rx  Rolling resistance force
RRL  Road load
RM  Aerodynamic rolling moment
RR  Ride rate of a tire/suspension system
Rφ  Roll rate of the sprung mass
s  Lateral separation between suspension springs
Sa  Aerodynamic side force
So  Spectral density of white-noise
SD  Stopping distance
t  Tread
ts  Length of time of a brake application
Ta  Torque in the axle
Tb  Brake torque
Tc  Torque at the clutch
Td  Torque in the driveshaft
Te  Torque of the engine
Ts  Roll torque in a front suspension
Ts  Roll torque in a rear suspension
Tam  Ambient temperature
Tx  Torque about the x-axis
V  Forward velocity
Vw  Ambient wind velocity
Vf  Final velocity resulting from a brake application
Vo  Initial velocity in a brake application
w  Tire section width
W  Weight of the vehicle
LIST OF SYMBOLS

$W_a$ Axle weight  
$W_d$ Dynamic load transfer  
$W_f$ Dynamic weight on the front axle  
$W_r$ Dynamic weight on the rear axle  
$W_{rr}$ Dynamic weight on the right rear wheel  
$W_{fs}$ Static weight on the front axle  
$W_{rs}$ Static weight on the rear axle  
$W_y$ Lateral weight transfer on an axle  
$x$ Forward direction on the longitudinal axis of the vehicle  
$y$ Lateral direction out the right side of the vehicle  
$YM$ Aerodynamic yawing moment  
$z$ Vertical direction with respect to the plane of the vehicle  
$X$ Forward direction of travel  
$Y$ Lateral direction of travel  
$Z$ Vertical direction of travel  
$Z_r$ Vertical displacement of the sprung mass  
$Z_u$ Vertical displacement of the unsprung mass

$\alpha$ Tire slip angle  
Coefficient in the pitch plane equations  
$\alpha_{cw}$ Aerodynamic wind angle  
$\alpha_d$ Rotational acceleration of the driveshaft  
$\alpha_e$ Rotational acceleration of the engine  
$\alpha_w$ Rotational acceleration of the wheels  
$\alpha_x$ Rotational acceleration about the x-axis  
$\beta$ Sideslip angle  
Rotation angle of a U-joint  
Coefficient in the pitch plane equations  
$\gamma$ Camber angle  
Coefficient in the pitch plane equations  
$\gamma_g$ Wheel camber with respect to the ground  
$\gamma_b$ Wheel camber with respect to the vehicle body  
$\delta$ Steer angle  
$\delta_c$ Compliance steer  
$\delta_i$ Steer angle of the inside wheel in a turn
δ₀  Steer angle of the outside wheel in a turn
Δ   Off-tracking distance in a turn
ε   Roll steer coefficient
     Inclination of the roll axis
ζ   Moment arm related to tire force yaw damping
     Half-shaft angle on a front-wheel drive
ζₜₙ Damping ratio of the suspension
ηₜ Braking efficiency
ηₜt Efficiency of the transmission
η₉f Efficiency of the final drive
η₉tf Combined efficiency of the transmission and final drive
θ   Pitch angle
     Angle of a U-joint
θₚ Body pitch due to acceleration squat or brake dive
Θ   Grade angle
λ   Lateral inclination angle of the steer axis (kingpin inclination angle)
μ   Coefficient of friction
μₚ Peak coefficient of friction
μₙ Sliding coefficient of friction
ν   Wavenumber of road roughness spectrum
ξ   Fraction of the drive force developed on the front axle of a 4WD
     Fraction of the brake force developed on the front axle
     Rear steer proportioning factor on a 4WS vehicle
ρ   Density of air
υ   Caster angle of the steer axis
φ   Roll angle
φ   Road cross-slope angle
χ   Ratio of unsprung to sprung mass
ψ   Heading angle
ψ   Yaw angle
ω   Rotational speed
ωₚ Damped natural frequency of a suspension system (radians/second)
     Rotational speed of the driveshaft
ωₚ Engine
ωₖ Rotational speed at the input of a U-joint
ωₙ Undamped natural frequency of a suspension system (radians/second)
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