DOI: 10.1002/jst.16

Development of a freeride mountain bike suspension fork

Jeff Baltes[1,*], *Cory Sutela*[1] *and Rob Redfield*[2,†]

[1] *Colorado Development Center, SRAM Corporation, Colorado Springs, Colorado, USA*
[2] *Department of Engineering Mechanics, United States Air Force Academy, Colorado Springs, Colorado, USA*

For the benefit of engineers working outside the bicycle industry, this paper describes some engineering considerations related to the development of a new model full suspension bicycle fork. The impact of market forces on the development process is considered, and a description of various design tools currently in use is provided. A detailed model of a new fork travel adjustment feature is included, along with simulation results produced by this model. The paper also includes an overview of the laboratory testing resources that are used to ensure the robustness of contemporary bicycle components. © 2008 John Wiley and Sons Asia Pte Ltd

Keywords:
- bicycle design
- suspension fork
- bond graph
- travel adjust
- bicycle testing

1. INTRODUCTION

Contemporary high-performance mountain bicycles are designed to fulfill specific functional requirements. Suspension systems for these bicycles must similarly be adapted for their intended use. The use categories of mountain bicycles continue to evolve, but some generalizations can be made about most products and the terrain for which they are designed. Elite cross-country racers normally choose front and rear suspension systems to accompany frames, which are optimized more for lightweight than large bump attenuation or durability. Front forks for these bikes are typically set up with 80–115 mm of travel. All mountain (or 'epic' all day) riders normally favor more durable bikes with 100–150 mm travel forks. At the extreme end of required durability lies the freeride and downhill market sector. Users in this category ride (or at least attempt to ride!) drops and gaps much larger than the riders' standing height, and other technical terrain that was only dreamed of a few years ago. They desire extremely durable frames and suspension systems with front and rear travel of 160 mm or more. This extreme category of front suspension system is the subject of this paper.

RockShox (Colorado Springs, Colorado, USA) has manufactured front and rear suspension systems for bicycles since the early 1990s. Fork design has always been a core part of RockShox's operation, and techniques for optimizing for both durability and light weight have improved steadily since then, perhaps more so since the company was acquired by the component manufacturer Sram. In this paper, some of the modern design techniques employed by RockShox are described, including a computer-aided finite element structural analysis, advanced modeling of a novel two-position fully-active travel adjustment system, and modern bicycle-testing techniques. These concepts are presented in the context of some of the market factors which also heavily influence suspension design.

*SRAM, #150-1610, Garden of the Gods Road, Colorado Springs, CO 80907, USA.
†The contribution of Rob Redfield to this article was prepared as part of his official duties as a United States Federal Government employee.

2. PROJECT MISSION

The mission of the RockShox Totem new product development effort was to create a best in class freeride suspension fork. The Totem suspension fork project was targeted to increase the depth of RockShox's product offering and to create a 'halo' effect to influence sales of other suspension products. The team made critical decisions about the project's scope and schedule based on these expectations. The following sections highlight some of the design, analyses, and testing that were performed as part of this project.

2.1 Cross-Functional Development Team

A cross-functional product development team was assembled and committed to executing the Totem project. The team consisted of a team leader, product manager, and development engineering group. The team leader functioned as the overall project manager and focused primarily on areas relating to the project's schedule, risk, and profitability.

Figure 1. Totem test riders at the 2006 Freeride Competition in Saalbach, Austria. Photos courtesy Dirk Belling.

The product manager focused on areas relating to product definition, marketing plan, and selling price. The development engineering group focused on designing and producing the actual product. This included concept generation, design analysis, prototyping, verification testing, supply chain development, cost of goods management, manufacturing process development, and quality planning.

2.2 Freeride Bicycle Market

The Totem suspension fork was intended for the freeride bicycle market. Freeriding is defined as 'a style of mountain biking that celebrates the challenges and spirit of technical riding and downhilling'. [1] Freeriders have pushed the limits of what is possible on a bicycle. It is a diverse riding style that demands the most from riders and equipment. Ski area bike parks are becoming increasing popular with thrill-seeking bicycle riders. The use of chairlifts to rapidly transport riders and bikes to the tops of mountains has dramatically increased the amount of high-speed technical riding that is possible in a day. The bike parks are developing freeride-specific trails with man-made and natural features to provide challenge and skill-building opportunities as shown in Figure 1. Freeriders also pedal their bicycles to remote epic locations or repeatedly navigate dirt jumps, ladder bridges, or rock drops. The freeride bicycle needs to perform like a durable, downhill racing bike one day, and a light-weight, all-mountain cross-country bike the next.

2.3 Customer Needs and Product Definition

The foundational elements of the Totem were based on the needs of freeride customers. The product manager obtained customer feedback from freeride bicycle manufacturers, aftermarket distributors, professional athletes, and recreational users. The customer feedback was distilled into a concise product specification with ranked customer needs and corresponding technical definitions. The product specification was used to guide the team's efforts throughout the project.

The three top ranked customer needs of the Totem were superior durability, oversize style, and low weight. The team technically defined superior durability as strong, stiff, consistent, and reliable. Oversize style was technically defined by the use of a 40-mm diameter stanchion tube as the foundation of the structural design. This became the defining feature of the Totem. Low weight for a best in class freeride fork was agreed to be less than 2633 g (5.8 lbs). These three requirements ultimately established the basic structure of the suspension fork. The team worked on a product that would employ a conventional single-crown structure and be capable of providing maximum suspension stroke of 180 mm.

The customer feedback also indicated that the Totem should be offered in a variety of spring system choices to satisfy a wide user base. The team decided on three distinct spring systems: (i) many customers indicated that a successful freeride fork must have an adjustable travel system that allowed for longer and shorter suspension strokes to optimize performance for different situations. The team developed a new 'two-position air' spring system to address this need. This system is described in detail later in this paper; (ii) customers concerned with a lower-weight product suggested the use of proven RockShox air-spring technology typically found in smaller cross-country racing forks. Air springs also allow for easy spring adjustment via a hand held air pump; and (iii) more traditional customers preferred the simple reliability and smooth feel of a coil spring system. All three systems were developed and made available as options on the Totem.

Customers also desired a damping system that allowed for a high level of performance and adjustability. The team determined that the damping system needed to provide rebound and compression damping with parallel flow low- and high-speed circuits to meet the demanding conditions of use. The compression and rebound damping needed to be

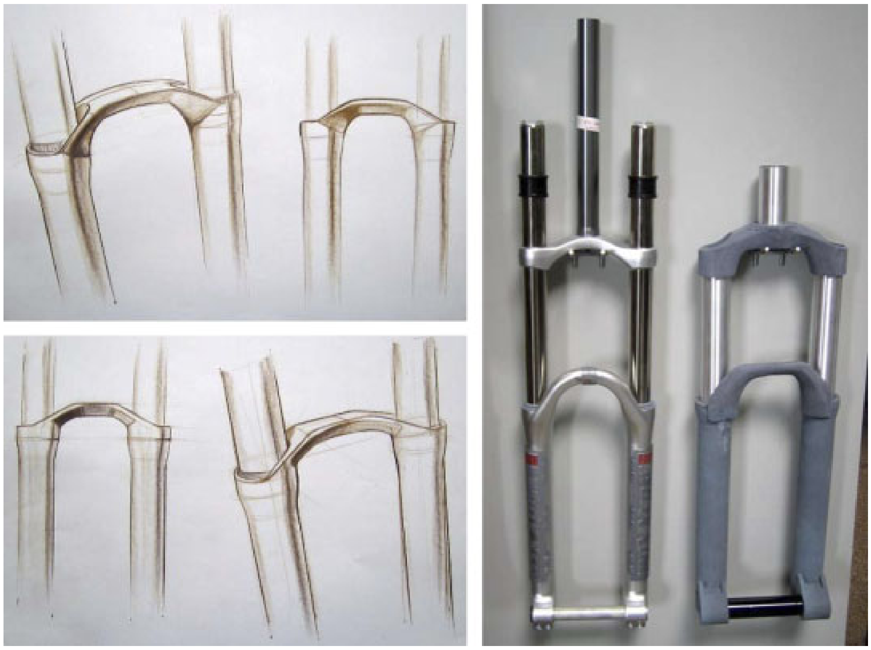

Figure 2. Industrial designer's sketches and hand-carved foam model.

externally adjustable so that the user could tune the damping to conditions. There was also a need to provide the user with an activated, highly-damped mode that would stiffen the suspension and allow for efficient pedaling without excessive bobbing. The team developed a damping system that met all of these requirements. It was also important to the customer that all user adjustment interfaces be of a high-quality feel. Anodized aluminum knobs with detent mechanisms were used for all externally adjustable features on the Totem.

3. STRUCTURAL DESIGN

Industrial designers and design engineers began parallel conceptual efforts to explore what was possible for the new product. The industrial designer's early efforts were intended to explore forms and styles of the desired product that would inspire the freeride customer. The industrial designer quickly developed possible forms of the Totem using paper sketches, foam models, and 3-D cad software. Examples are shown in Figure 2. The design engineer's early efforts were intended to explore what was technically feasible and to predict key performance characteristics like weight, stiffness, and strength.

The finite element analysis (FEA) was used to gain a better understanding of the design's structural performance potential and areas of risk. The Totem product was developed using commercially available finite element analysis software. The FEA analysis was created to compare the new Totem design to an existing RockShox fork model with extensive test and field-use history. This gave the design team confidence in the analysis and results. An effort was made to use FEA as a means of rapid design iteration and evaluation. Computer Aided Design (CAD) models were simplified as needed to reduce the analysis time. Typically, analysis started on a single component and then was built upon to create a higher-level assembly analysis.

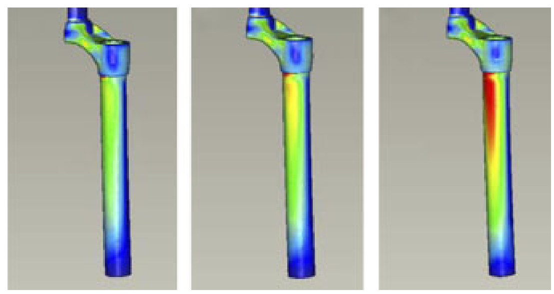

Figure 3. Frontal bending moment load analysis on a partial chassis assembly showing the effect of stanchion tube wall thickness on stress.

An example of a fundamental suspension fork FEA used for Totem was a bending moment analysis that simulated horizontal loads applied to the structure. An example of this type of loading would be riding the bike straight into a large obstacle like a large rock or log. The analysis constraints simulated the suspension forks' connection to the bike frame at the headset bearing interface surfaces. The analysis force loading was applied to a point at the center of the wheel axle. The direction of the load vector is perpendicular to the sliding plane of the fork in either positive and/or negative directions. This type-bending analysis was used primarily to evaluate the steer tube, fork crown, stanchion tube, and lower slider. The analysis was also used to predict the overall bending stiffness and strength of the new suspension fork design. Two examples of bending analyses are shown in Figures 3 and 4.

A second type of FEA analysis used for the development of the Totem was a torsion loading that simulates rotational steering input loads. An example of this type of loading would be steering the bicycle out of a deep rut that prevents the wheel from freely turning to the side. The analysis constraints simulated the suspension forks connection to a fixed wheel hub.

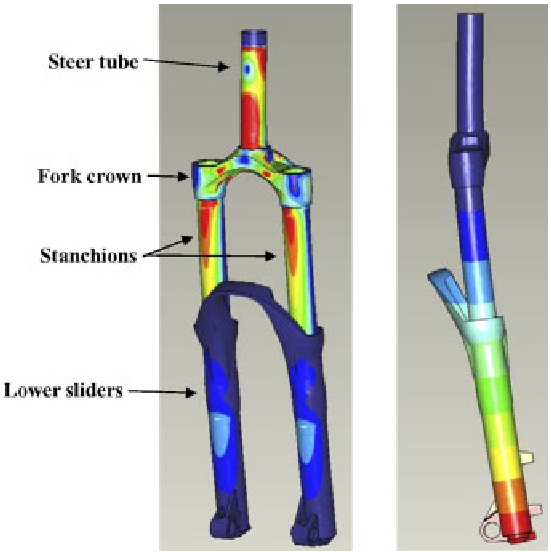

Figure 4. Frontal bending moment load analysis on a fork chassis assembly showing deflection and stress.

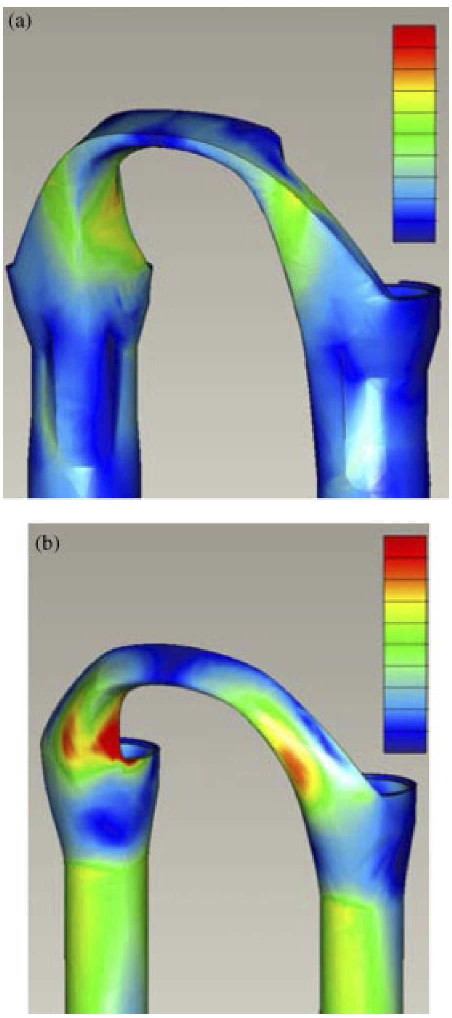

Figure 5. Torsion load stress analysis comparing the RockShox Totem (a) and RockShox BoXXer (b) lower sliders.

The analysis moment loading was applied to a point on the steering axis. The torsion analysis was used primarily to design

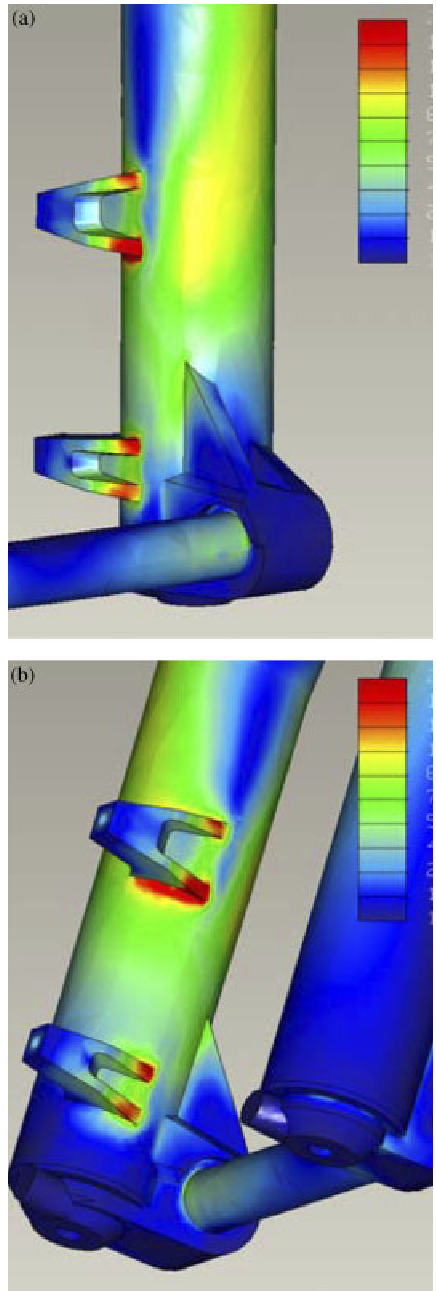

Figure 6. Combined loading brake effect analysis showing stress on the lower slider and axle.

the lower slider wheel attachment features and connecting brace. A comparative torsion analysis is shown in Figure 5.

A third type of FEA analysis used for designing the Totem was a combined bending and torsion loading that simulates disc brake reaction forces on the structure. Similar to the bending analysis, the constraints simulate the suspension forks' connection to the bike frame at the headset bearing interface surfaces. The combined loading consisted of a force vector applied to the wheel center perpendicular to the sliding plane of the fork, and a moment load about the axle center applied to the brake caliper mounting features. The magnitudes of the loads were based on RockShox's internal disc brake load test standards. Examples of a disc brake analysis are shown in Figure 6.

3.1 Materials

Some notable structural materials were used in the Totem design. The forged-fork crown was made from a proprietary AL 6066 alloy developed for use in pedal crank arms. This aluminum alloy has significantly improved tensile yield strength and elongation over the common AL 6061-T6 traditionally used in RockShox fork crowns. The seamless cold-drawn stanchion and steer tubes were made from a proprietary AL 7050 alloy developed specifically for RockShox suspension products. This aluminum alloy has high strength, toughness, and resistance to stress corrosion cracking. The die cast one-piece lower slider was made from a light weight Mg AM60b alloy. This magnesium alloy has good strength, high toughness, and can be cast into thin sections.

Figure 7. Functional prototype.

3.2 Functional Prototype

A complete functional prototype Totem suspension fork was constructed using machined prototype components. The functional prototype allowed users to actually test ride the new fork long before the major tooled components were available, as shown in Figure 7. The prototype was used to evaluate structural stiffness and disc brake compatibility. It was also an excellent way of demonstrating the impactful style and size of the Totem product.

3.3 Simulation Analysis of Two-Position, Travel-Adjust Air Spring

One of the key adjustment features of the Totem air suspension fork is the 'two-position air' system with its single port air-charging capability. Because the system is rather complex, a simulation model was developed to better understand the dynamics of its behavior. A simulation model of a mountain bike rear shock is developed in a similar fashion [2].

3.4 Description and Operation

The hydraulically-controlled travel adjustment system is integral with the air spring. The system is contained in a single suspension fork stanchion and is schematically represented in Figure 8. The long-travel configuration in shown in the center of the figure, and the short-travel position is shown on the right.

Inside the stanchion, an air tube houses the suspension components. A rod, which is attached to the fork lower sliders

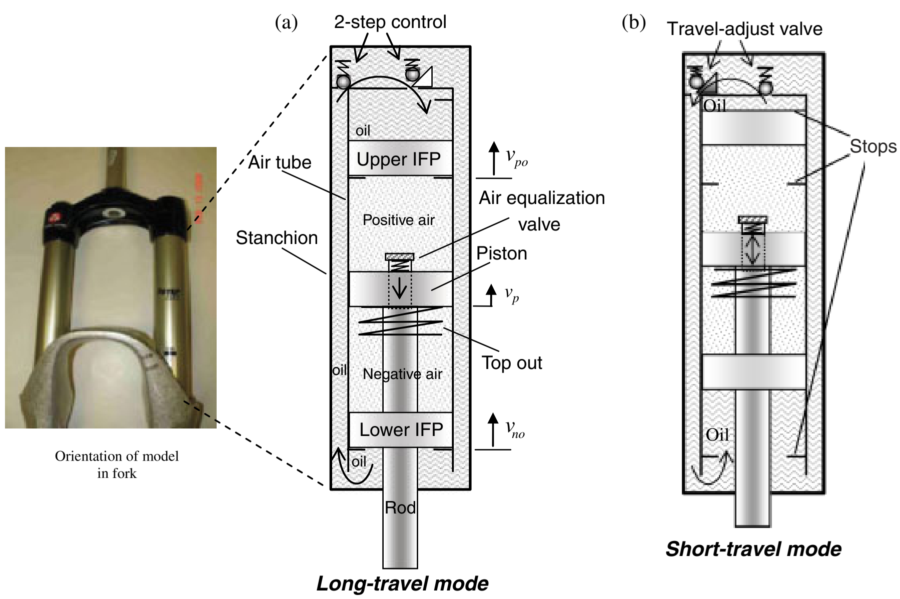

Figure 8. Air suspension and travel adjust in (a) long- and (b) short-travel mode.

and the bike axle, moves a piston in an air tube with *positive* air above the piston and *negative* air below. 'Positive' air supports the bike/rider load by acting to extend the fork. 'Negative' air acts in the opposite direction and is used to reduce the force required to initiate fork compression. This results in improved compliance over small bumps. Internal floating pistons (IFPs) separate the positive and negative air chambers from oil chambers in the top and bottom of the tube. The oil chambers communicate through an oil path in the annular area between the air tube and stanchion. A *top-out* spring provides a softer transition at full extension (when the fork *tops out*).

Nomenclature of the air suspension schematic include v_b and v_s which are the bike and sprung mass velocity, v_p which is the piston velocity, v_r and v_u which is the rod and unsprung mass velocity, and v_{po} and v_{no} which are the upper (positive) and lower (negative) floating piston velocities.

The piston is allowed a small amount of spring-controlled motion relative to the rod. This relative motion controls an air equalization valve. With near full-fork extension, the piston moves up on the rod, opening an air bypass between positive and negative air chambers. This equalizes the air pressures at full-fork extension which allows a single air source to pressurize both air chambers. The fork is charged through an air valve at the bottom of the hollow rod which allows direct pressurization of the positive side.

Travel is changed by actuating a bidirectional-travel adjust valve in the stanchion tube. The valve allows flow between the upper and lower hydraulic chambers in one direction or the other. In the long-travel mode, hydraulic fluid may only flow from the lower oil chamber to the upper chamber. An unloaded, pressurized fork forces the piston down and extends the fork until the upper IFP hits a mechanical stop. Except for small hydraulic compliance, the upper IFP will stay on this stop in use. The lower IFP rests against its lower stop on the seal head between the air tube and stanchion.

For short travel, the position of the travel-adjust valve is reversed, allowing oil flow from the upper to lower oil chamber. The rider applies body weight to the fork which forces the piston up, causing the upper IFP to shuttle toward its upper stop. The lower IFP also rises to a new position above its lower stop. Because of the presence of the rod, the cross-section of the lower oil chamber is smaller than the upper chamber, and the lower IFP moves up further than the upper IFP. The overall effect is a slight increase in the equilibrium air pressure.

3.5 Dynamic Model

A dynamic model of the two-position air spring was constructed to evaluate the behavior of the system during realistic transient scenarios. Both air chambers were modeled as variable mass, energy, and volume spaces with mass and energy flow through the equalization valve. Both compressibility and extensibility of the hydraulic oil were included with orifice communication through the check values. Mass and friction were considered for the IFP and the piston. The top-out spring and IFP stops were also included in the model.

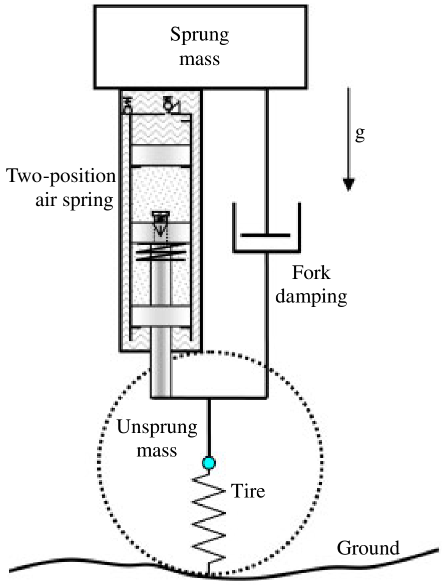

Figure 9. System model of suspension fork and bike/rider.

The entire air spring system model was embedded into a suspension fork system model that includes sprung (bike and rider) and unsprung (wheel and suspension lowers) masses and tire compliance. The input to the model is a variable ground profile. A schematic of this system is shown in Figure 9.

A bond graph representing the key energetic effects of the combined system is shown in Figure 10. Bond graphs are concise, graphic representations of the dynamic interactions in a system. Karnopp *et al.* provide a fine introductory and advanced reference for the modeling of engineering systems by the bond graph approach [3]. Bond graphs support energetically rational models (guarantee energy conservation) and demonstrate system causality (subsystem input/output compatibility) transparently. Bond graphs excel at multi-domain modeling, such as this suspension system that incorporates mechanics, hydraulics, and pneumatics.

The bond graph includes I and C elements that represent kinetic and potential energetic storage (inertias and spring-like subsystems); R elements that model losses from damping (friction and valves); and Se and Sf (source) elements, such as weight and ground unevenness. The bond graph structure includes power bonds (half arrows), zero and one junctions, and transformers that properly establish continuity and kinematical constraints. Lastly, the dashed arrow represents the signal flow of the equalization value spring position in controlling the opening area between the two air chambers.

Nomenclature in the bond graph not previously defined include ground velocity v_g, relative velocities between the bike and upper IFP, $v_{po/b}$, between the bike and rod, $v_{r/b}$ and between the bike and lower IFP, $v_{no/b}$. A_{po}, A_{pa}, A_{na}, and A_{eq} are areas of the upper IFP, top piston area, bottom piston area (also lower IFP area), and equalization valve flow area. Pressures P_{po}, P_{no}, P_{pa}, and P_{na} are for the upper oil, lower oil, positive air and negative air respectively. Q_{2p} is oil volumetric flow rate, $\dot{V}_{pa}$ and $\dot{V}_{na}$ are volume rates of positive and negative air chambers, $\dot{E}$ is energy rate, and $\dot{m}$ is mass rate.

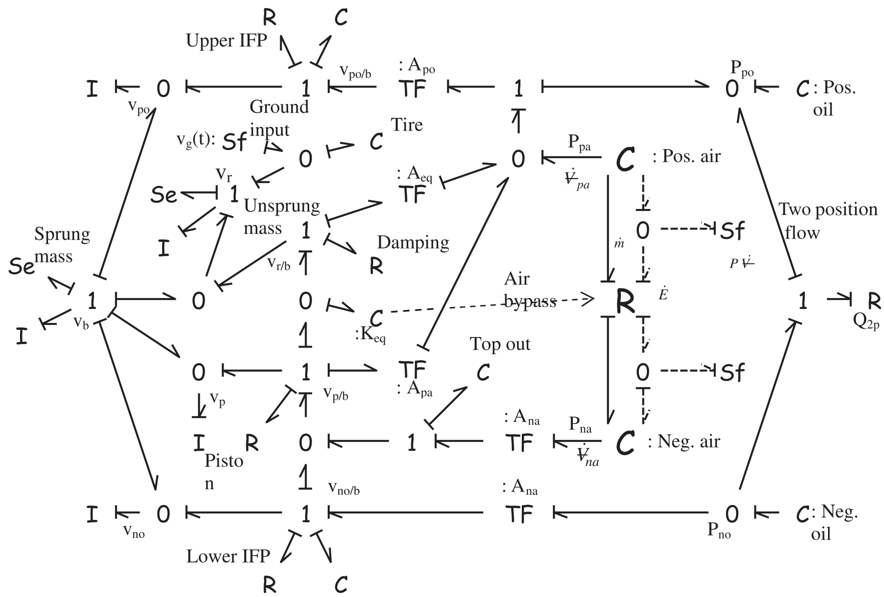

Figure 10. Bond graph of suspension system. IFP, internal floating pistons; Neg., negative; Pos., positive.

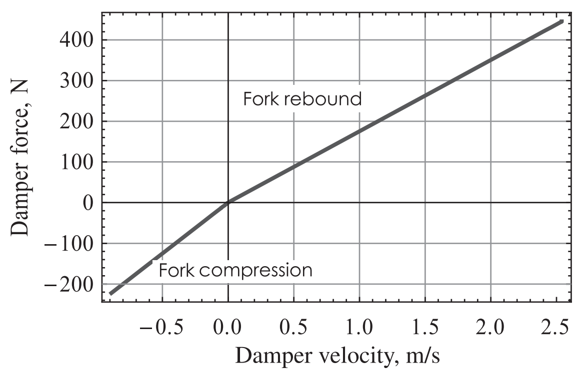

Figure 11. Fork damping. Relative velocity *vs* damping force.

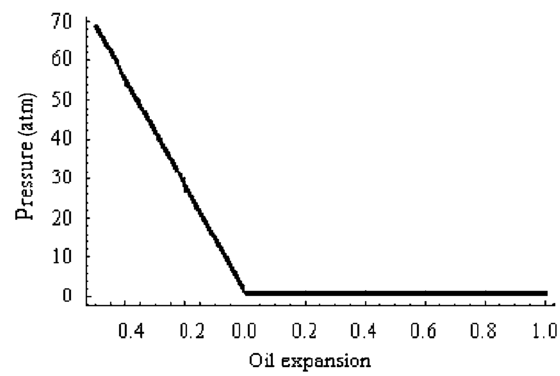

Figure 12. Model pressure response to changes in oil volume.

3.6 Model Quantification

A set of coupled, non-linear, differential equations is extracted from the bond graph. Constitutive relationships are defined for the system elements based on their physical behavior. Springs and mechanical stops are modeled as piecewise linear stiffness elements. Stiffnesses are measured or approximated. The tire is modeled with a stiffening compression force and zero tensile force. The top-out spring is represented similarly. A typical fork damper has independent compression and rebound oil flow paths, and rebound damping forces are typically higher than compression forces. The behavior of the compression and rebound circuits was measured experimentally, and simplified into a piecewise linear relationship, as shown in Figure 11. The transition between the two states was smoothed to ensure better numerical behavior.

The air chambers are variable volume, mass, and energy accumulators. Work is done by the moving piston, and both mass and energy are transported when the air equalization valve is open. Heat transfer is neglected. The constitutive laws for the air chambers were derived from the perfect gas law as shown in the following equations:

$$U = mC_vT$$
$$P = \frac{RU}{c_vV} \tag{1}$$
$$T = \frac{U}{c_vm}$$

where U is internal energy, m is mass, c_v is specific heat, T is absolute temperature, P is absolute pressure, R is the gas constant, and V is volume. Volume changes are based on the motion of the piston and rod relative to the air tube. Mass flow rate between the air chambers ($\dot{m}$) is assumed isentropic and thus is limited to sonic velocity [4]:

$$\dot{m} = C_dA_o\sqrt{\frac{2\gamma\rho p_u}{\gamma-1}}\left(\frac{p_d}{p_u}\right)^{1/\gamma}\sqrt{1-\left(\frac{p_d}{p_u}\right)^{(\gamma-1)/\gamma}} \tag{2}$$

where C_d is the discharge coefficient, A_o is the throat area, P_u and P_d are upstream and downstream pressures, ρ is upstream density, and γ is the ratio of specific heats. Energy rate comes

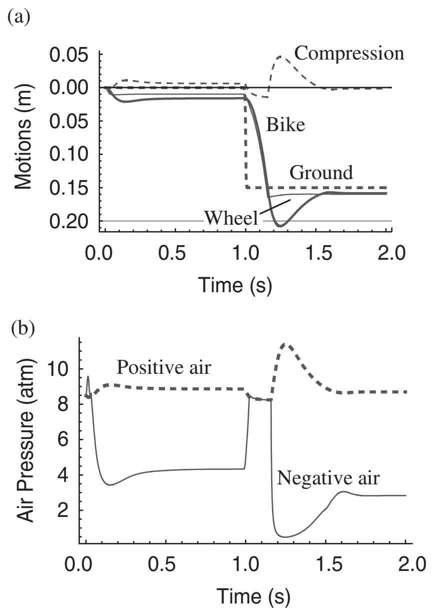

Figure 13. (a) Suspension motion and (b) air pressure for motion down a curb.

from both work done and convection with mass flow:

$$\dot{E} = \dot{m}u - P\dot{V} \tag{3}$$

where $\dot{E}$ is energy rate, u is specific internal energy (U/m), and $\dot{V}$ is volume rate.

The hydraulic oil was modeled as very stiff in compression (1000 psi changes volume by 0.5–1%) and soft in tension. The constitutive behavior of the oil is shown in Figure 12. Oil expansion is on the abscissa because it is the independent variable in the pressure relationship. Flow between the oil chambers is treated as the orifice flow based on discharge coefficient, valve opening, and pressure ratio.

4. SIMULATION RESULTS

Often, static thinking about the response of a system will leave out or incorrectly predict dynamic behavior. Simulations were examined to gain insight into the dynamics of the model and see if any non-intuitive dynamic behavior could negatively affect fork performance.

4.1 Small Drop in Long-Travel Mode

The first simulation performed consisted of the suspension system in long-travel mode rolling off a curb. The curb is a 15-cm negative step and is shown in Figure 13, labeled 'ground.' The other displacements shown are the fork crown, which moves with bike/rider vertical motion, the wheel, and the fork compression. In all cases, the initial conditions were for all fluid flows set to zero, and equal pressure of 100 psi in the two air chambers. The horizontal bike velocity was 5 m/s.

The first 0.5 s show the suspension reaching equilibrium under the weight of the rider; the wheel and crown move down

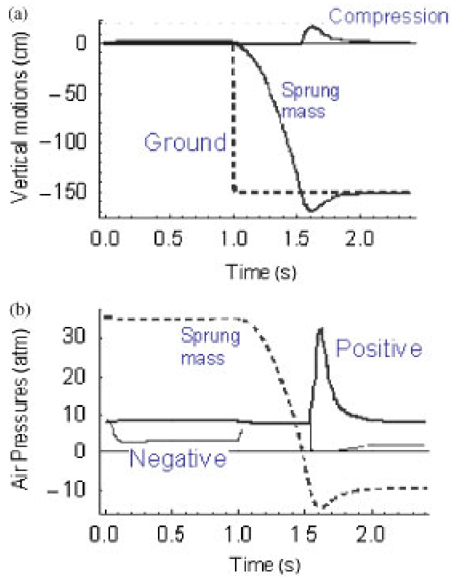

Figure 14. Long-travel over large drop. (a) Major motions and (b) air pressure.

and the suspension compresses. When the wheel rolls off the curb, the crown drops as the suspension briefly extends. When the wheel hits the ground, the suspension compresses and the transient dies out to steady state. Figure 13(b) shows the pressures during the transient. Before the drop, the rider's weight causes positive air to gain pressure and negative air to lose. During the drop, the suspension extends to full travel, and the air equalization valve opens equalizing pressures. When the wheel hits bottom, positive air pressurizes further and negative air expands and loses most of its pressure.

This is a relatively small ground input to the model and gives confidence that the model predicts system behavior correctly, in a qualitative sense. More extreme ground inputs follow.

4.2 Large Drop in Long-Travel Mode

The selected model responses of a fork set to long-travel mode simulating riding off a 1.5 m drop are shown in Figures 14–16. The initial conditions remain as before. At approximately 1 s, the bike reaches the edge of the drop, and at just past 1.5 s, the tire comes in contact with the ground at the end of the drop.

The elevation drop of 1.5 m, the vertical bike motion (sprung mass), and the suspension compression are shown in Figure 14(a). For the first second, the sprung mass and compression settle under a compressed suspension and tire. As the bike leaves the drop, the suspension extends slightly. At the bottom of the drop, the suspension compresses, dissipates the energy, and finds its way back to steady state.

The positive and negative air pressures are shown in Figure 14(b), and include the sprung mass travel as a reference trace. Initially, the positive pressure increases slightly and the negative decreases substantially. This is due to the difference in chamber volumes. At the drop, the suspension extends, the air valve opens, and the pressure equalizes between the chambers.

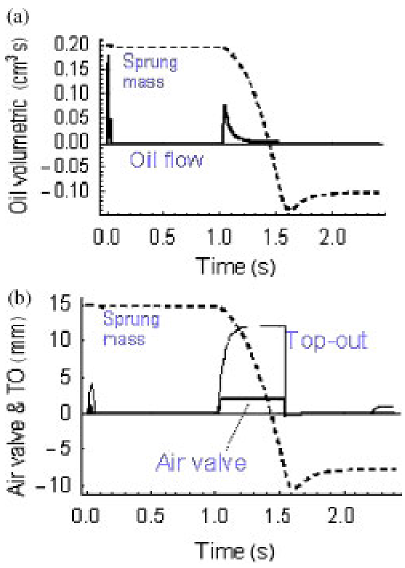

Figure 15. Long-travel over large drop. (a) oil flow, air valve, and (b) top out (TO).

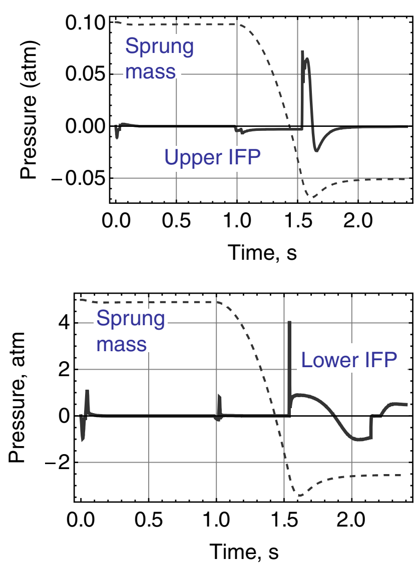

Figure 16. Long-travel response. Internal floating piston differential pressures.

At the drop bottom, the positive pressure rises substantially to approximately 32 atm, and the negative pressure drops toward zero. Both pressures recover somewhat at the end of the dynamic, but they both arrive at different pressures than before the drop. This is due to air transfer between air chambers.

Oil flow, air valve motion, and top-out spring action all superimposed with the sprung mass motion are shown in Figure 15. Oil flows from negative to positive oil chambers at the beginning of the simulation when air chambers have equal initial pressures, forcing the fork to extend slightly and thus compressing the oil in the lower chamber. Oil also flows while the fork is in the air and extends fully, before it hits the bottom of the drop. The air valve opening as the fork extends during the drop is shown in Figure 15(b). The top-out spring engagement is shown during the drop and at the end of the transient. Because air flows

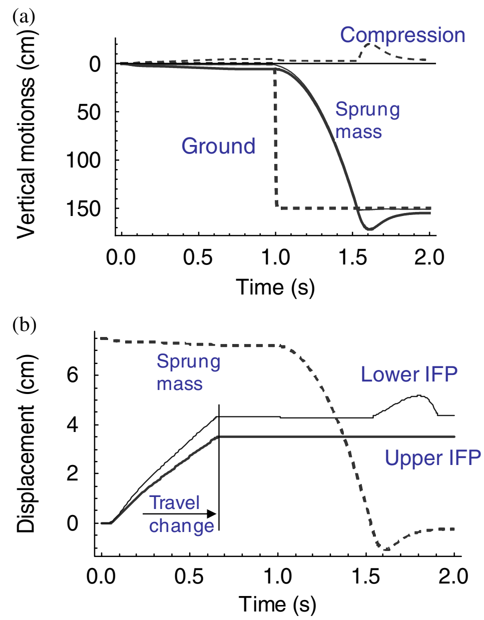

Figure 17. Short-travel response. (a) Ground elevation and bike and wheel motions and (b) compression and internal floating piston (IFP) motions.

out of the negative chamber during the drop, the fork compresses slightly and causes the top-out spring to be compressed at equilibrium (with the sprung mass sitting on the fork).

The differential pressures across the IFP are shown in Figure 16. When these pistons float between stops (hard stops or top out), pressure differentials stay near zero. Notice that these pressure differentials are normally very small, except for a large spike in lower IFP differential pressure and a non-zero ΔP at the final equilibrium. In this condition, the lower IFP contacts the top-out stop and can sustain significant differential pressures. The differential pressure spike coinciding with the drop bottom indicates a large *jerk* (derivative of acceleration.)

4.3 Large Drop in Short-Travel Mode

The selected model responses of a fork set to short-travel mode ridden off a 1.5 meter drop are shown in Figures 17–20. The initial conditions are with the rider off the bike, the air pressures equal, and the bike just switched to short-travel mode. At approximately 1 s, the bike reaches the edge of the drop, and at just past 1.5 s, the tire comes in contact with the ground at the end of the drop.

The 1.5-m elevation drop, the sprung mass motion, and the degree of suspension compression are shown in Figure 17(a). During the first second, the bike reaches equilibrium as both the suspension and tire compress, and the suspension travel changes. As the bike leaves the drop and falls, the suspension extends to its short-travel topped-out position. At the bottom of the drop, the suspension compresses, dissipates the energy, and returns to steady state.

The sprung mass motion for reference and the position of both IFP are shown in Figure 17(b). The suspension first compresses as the rider settles into the suspension and the fork moves to its short-travel position; the upper IFP moves linearly to its upper stop (3.5 cm up), and the lower IFP moves off its stop and up a little over 4 cm. At the drop, the amount of compression decreases as the suspension expands and the IFPs stays in place. At the end of the drop, the suspension compresses significantly, the upper IFP remains on its upper stop, and the lower IFP briefly rises approximately 1 cm creating a vacuum in the lower oil chamber.

The positive and negative air pressures during the drop are outlined in Figure 18(a). As the suspension initially

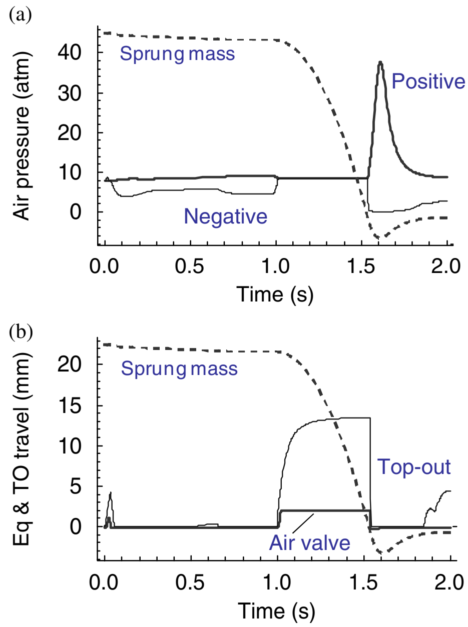

Figure 18. Short-travel response. (a) Air pressures and (b) equalization valve (Eq) and top-out (TO) spring motions.

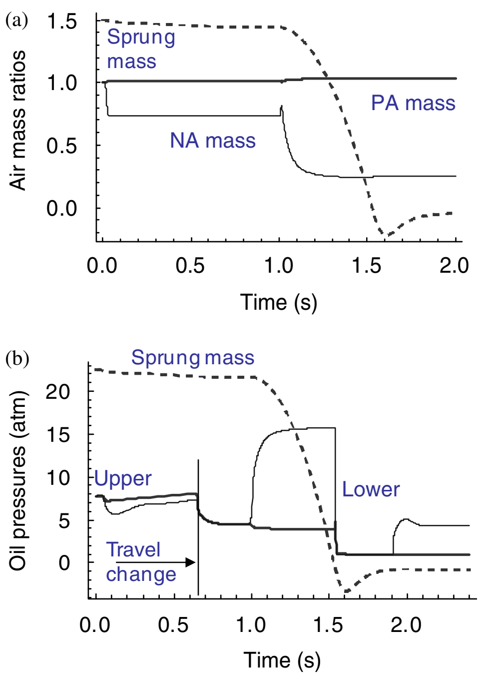

Figure 19. Short-travel response. (a) Air mass ratios and (b) oil pressures. NA, negative air: PA, positive air.

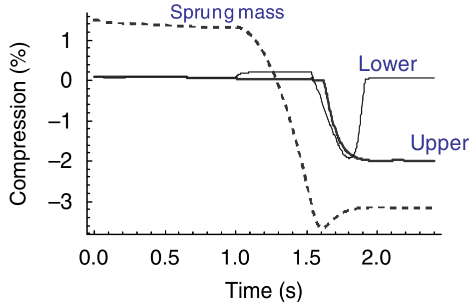

Figure 20. Short-travel response: oil compression.

compresses, positive air pressure rises by approximately 1 atm, and the negative pressure drops by 4 atm. When the suspension extends during the drop, the air equalization valve opens (Figure 18(b)), and the two air chambers equalize pressure until the bike makes contact with the ground. The valve then closes and the positive pressure rapidly raises to 38 atm, and negative pressure drops as low as 0 atm (gage). This positive pressure is 6 atm more than the pressure produced by the same transient when the fork was in long-travel mode. Top-out spring engagement is also seen during the drop and as the system recovers to equilibrium. This is due to the air that has left the negative air chamber as will be seen shortly.

The air exchange between positive and negative chambers, where air mass ratios are relative to the initial mass at time zero, is shown in Figure 19(a). In the initial milliseconds, the suspension extends slightly, opening the air valve and equalizing the pressure between the negative and positive chambers. At the drop, air flows initially from the higher pressure of the positive chamber to the negative. With the extension of the fork, the negative side quickly pressurizes and exceeds the positive; flow then reverses, reducing the negative side air mass. Air pressures equalize in the extended fork during the drop leaving the negative side with 25% of its initial mass.

The oil pressures in Figure 19(b) show an initial difference as the fork moves to its short-travel mode. When the upper IFP hits the upper stop at 0.7 s, the oil stops moving and the oil pressures equalize and drop. The drop in pressure is due to the oil expanding as the lower IFP lifts, increasing the lower oil chamber volume. As the bike moves over the drop, the fork extends, compressing the top-out spring and increasing negative oil pressure. At the end of the drop, the positive pressure rises briefly, causing the oil valve to open and allowing some oil to move into the lower chamber; this reduces oil pressure in the upper chamber. Lastly, the lower oil chamber pressure increases because the lower IFP is floating; however, the upper oil chamber cannot regain pressure unless the check valve leaks back.

Finally, in Figure 20 the percentage volume change of the oil chambers is shown, where a positive percentage denotes compression and a negative percentage denotes tension (vacuum). Both are in compression until the end of the drop. The lower chamber pressure becomes subatmospheric as the lower IFP lifts. This pressure recovers at the end of the transient. The upper chamber pressure becomes subatmospheric after the initial pressure from the drop force moves oil through the check valve from positive to negative. When the upper IFP relaxes off its stop, the upper oil chamber remains in a vacuum indefinitely.

4.4 Simulation Interpretations

Not only can simulation results, like those discussed, give predictions for design variables like pressures, flow rates, and shaft speeds, they can also give insight into dynamic influences that cannot be easily determined by intuition and experience. For example, differential pressures greatly increase when IFPs contact stops and top-out springs. These pressures are what drive oil or air leaks.

Oil chambers that achieve a vacuum pull entrained gasses out of the oil. Upon recompression, most air is re-absorbed, but some can emulsify and add compressibility to the oil and cause cavitation in valve or orifice flow. Avoiding vacuum may be important is certain instances.

The equalization air valve is primarily designed to allow air to flow between chambers upon charging and this occurs with the fork at full extension. Simulation shows that this valve opens in other circumstances allowing air to flow when perhaps not intended. Whether this is a significant performance issue can be determined, and other strategies for air charging to both chambers can be developed.

Next we consider testing to verify performance and meet standards.

5. TESTING OF THE TOTEM

5.1 Challenges

To verify the integrity and performance of the Totem, the development team addressed two types of testing challenges: (i) standard challenges that are common to any new front suspension development; and (ii) challenges unique to this project.

The validation of many fork development projects borrows heavily from the performance of existing products, which can provide several years of actual field data to support design decisions. Questions that a RockShox development team must typically answer during validation include:

- How can the overall durability a new fork be defined and quantitatively assessed? To answer this, a team must consider both 'normal' use and expected misuse of the product.
- How can a product's entire lifetime be condensed into accelerated tests that can be completed in time to make necessary design changes?
- How can the performance of a new fork be evaluated, considering the application of this single component into the complete bicycle system?

The answers must consider a variety of frame designs from many manufacturers.

The Totem project deployed new structural geometry and boasted new performance features that could not be validated with test data from existing products. Design features unique to the Totem project which introduced new testing challenges included:

- The use of 40-mm diameter stanchions. The increase in stiffness-to-weight ratio over the previous standard (32-mm diameter stanchions) achievable with this design choice was compelling to the team. However, evaluation of these tubes and the associated subcomponents (seals, sliding bushings, top caps, damper assemblies, pistons, and shafts) could not be achieved by relying on previous test data. Structural evaluation of these components would require construction of new test fixtures. Performance evaluation required thorough testing of every new component. For example, the Totem main oil seal was the first entirely new seal developed by RockShox in several years, yet would be required to meet the same performance standards as a seal that had been used for several years on multiple fork platforms.
- The introduction of a new adjustable air spring system. The two-position air assembly would allow users to quickly and easily switch between two fully-active travel settings, but how could the team ensure satisfactory durability of this system?
- The use of a new steer tube standard. Like the use of 40-mm stanchions, the primary advantage of the new industry standard 38.1 mm diameter steer tube over the conventional 28.6 mm was a dramatic increase in strength and stiffness. The Totem project was to be offered with the option of either steer tube size. The result was a nearly doubling of the structural testing requirements and requirements for new test fixtures and interfaces with existing test machines
- Longer travel than any existing single-crown fork. Fortunately, the additional challenges presented by this design feature did not complicate testing significantly, because testing resources were already in place to evaluate the long-travel double-crown RockShox BoXXer fork.

5.2 Overview of Testing Resources

5.2.1 Field data acquisition

How were the challenges of verifying the Totem design addressed? The team had many engineering resources at its disposal. First, to allow insight into the structural requirements of its forks, RockShox makes use of a lightweight field data acquisition system, as shown in Figure 21. Sensors attached to similar fork models or early prototypes feed force and travel

Figure 21. Portable data acquisition system.

data into a compact 10 channel A/D converter and data storage unit. The measured data can be used to define multi-axial durability tests that are reproduced later in a laboratory setting (these durability tests are described in more detail later). The data also reveal the maximum loads encountered during real riding, which are used to set acceptance criteria for single-axis ultimate load tests in the lab. Finally, the data can be distilled using frequency analysis to specify appropriate force levels and cycle counts for laboratory fatigue tests.

5.3 Industry Standards and Standard RockShox Tests

Another testing resource used to complete the Totem verification plan was the application of established bicycle industry test standards. The most significant of these were the Central European Norme (CEN) and the American Society of Testing and Materials (ASTM) standards. Both of these groups produce well-documented test procedures specified by testing experts related to the bicycle industry: a variety of manufacturers, consultants to the industry, and researchers from academic settings whose research programs include bicycle testing. The standards put forth by CEN and ASTM cannot be considered the final word in the required testing of a new suspension fork. They define relatively basic requirements for structural integrity related to the safety of consumers. They do not address performance issues specifically, and they do not in general reflect the requirements of specific segments of the mountain bike market such as 'freeride'. Their use comes in providing a starting point, a minimum standard of performance for any fork that can be offered on the market. As an example, Figure 22 shows the Totem fork installed on a frontal impact tester suitable for determining conformance to CEN and ASTM standards. In this test, a 22.5-kg mass is released from a series of prescribed drop heights. The fork is inspected for damage after each drop. A successful completion of this test is required in order to certify a fork for release into the market. In fact, RockShox's internal standards for frontal impact are higher than the minimum levels set out by the ASTM and CEN. Test results from the Totem project in the context of both internal and external standards are provided later in this section.

Figure 22. Totem fork installed on a frontal impact tester.

5.3.1 Component level testing

The structural performance of a complete suspension fork depends on the strength of its component parts, most significantly the crown, steer tube, stanchions, and lower sliders. The synergy between these components is difficult to predict because of the complex geometries involved and the variety of materials. For this reason, performance of the complete suspension fork could not be predicted solely from the performance of each component. Nonetheless, the verification of new design features was accelerated with component level testing. The major structural elements of the fork were developed separately, and the team was able to evaluate design choices in some components without waiting for all components to be assembled into a complete fork. Specifically, fixtures were built to assess the strength of prototype crown–steerer–stanchion assemblies, before the design of the lower sliders was complete. A consideration favoring this approach is the fact that suspension fork lower sliders are typically manufactured using relatively expensive casting tools with longer lead times. Machined prototypes are difficult to produce, yet do not have the same mechanical properties as cast ones. It was not practical to manufacture a 'production intent' lower slider in order to evaluate the ultimate and fatigue strength of a new steer tube or the larger stanchions.

Oil seal development was also required several months before the actual lower sliders were available for full-fork testing. Several iterations of seal design were rapidly evaluated using this 'component level' approach.

5.3.2 Hydraulic test bed, frontal impact, and failure mode

An important testing resource at the team's disposal was a single axis servo-hydraulic test bed with advanced damper analysis software. The test machine, shown in Figure 23, allows the precise control of the actuator up to a force of 15 kN, with shaft speeds up to 2500 mm/s. For thorough evaluation of the damper system offered on the Totem fork, higher operating speeds measured in the field were recreated, albeit at lower forces. These were achieved using a 3:1 leverage ratio rocker arm on a fixed base.

Frontal impact and fatigue tests were also performed on this machine to supplement the CEN and ASTM standard tests described earlier and to ensure safe failure modes under expected riding conditions. Normalized results from actual stiffness and frontal impact tests performed on this machine are provided in Figure 24. The stiffness and energy absorption values at the

Figure 23. Servo-hydraulic test machine.

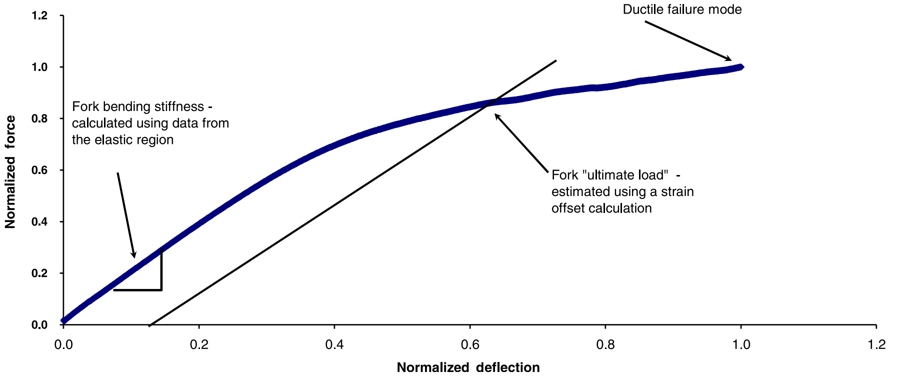

Figure 24. Bending stiffness and ultimate load.

beginning of the test have been shown to be the most important factors in preserving control of the bike during a frontal impact [5]. The frontal impact structural testing showed that the fork was sufficiently stiff and was capable of absorbing enough energy before deforming; a rider would be ejected from the bike long before the fork lost structural integrity.

Since under these conditions a rider would be thrown from the bike before the fork deformed, the mode of failure might not seem terribly important. However, a foreseeable misuse of this product includes riding it after it had been permanently damaged (by, for example, accidentally driving the fork into a garage on top of a car, or dropping the bike off a chairlift). Design changes were made to the fork after a few prototypes showed a brittle failure mode under conditions of very extreme frontal impact.

Figure 25. Two-axis fork simulator.

5.3.3 Two-axis simulator

Ultimately, the performance of sealing components in the Totem's main structure and damper assemblies required evaluation in a complete fork. Rigorous durability testing was required to ensure that sealing performance would not degrade over the life of the fork. To accelerate this durability testing, RockShox uses a two-axis hydraulic simulator. The simulator duplicates both the normal axial compression of the fork and a load perpendicular to fork compression, applied at the front axle, as shown in Figure 25. The combination of loading in these two directions has historically been successful in evaluating the durability of sealing components. The loads in both axes can be regular waveforms (most often sine waves) or duplicated from data acquired on the bike. In this way, harsh conditions of use (and even misuse) can be characterized from field test ride data, and then reproduced in the lab. Structural, damping, and sealing performance tests can be performed before and after several simulations in order to evaluate durability.

6. CONCLUSION

The development of new, sophisticated, and high-end components for mountain bikes is a long and involved process.

This paper has touched upon some key elements of the process, giving insight into the teamwork and varied expertise and effort required for a successful product.

The goal of the Totem project was the production of a best in class, freeride suspension fork. Development required the contributions of product managers, designers, and many engineers and technicians. Customers' needs were determined, virtual and real prototypes created, designs were analyzed, and much testing and iteration was performed before the fork was ready for production. Among the more significant engineering contributions was the structural design/analysis using CAD and FEA support, the material selection, the seal design, the system modeling of complex dynamics, and the breadth of testing (field and laboratory) to prove that the design meets external and internal standards.

The Totem project was completed on schedule in July 2006. After its initial year of mass production, the RockShox Totem freeride suspension fork was chosen as one of the best new products of 2007 by Mountain Bike magazine. The following statement could be considered objective evidence that the development team succeeded in creating a best in class product:

'ROCKSHOX Totem Solo Air, $1060 This is a fork of contradictions: It has huge, 40 mm stanchions and 7 inches of travel but a single crown; it looks massive in every way (especially the 1.5-inch steerer tube), yet it weighs fewer than 6 pounds; there are 20 mm thru-axle dropouts but the Maxle QR is easier and faster to use than bolt-ons. And even though the spring is air (you can also opt for coiled steel) the Totem is a fork we love to see on the front of our freeride bikes because it possesses all of a freeride fork's most critical characteristics–it's stiff, light, highly tunable, and confidence-inspiring. Bottom line: This fork's ride quality is very refined'.

Mountain Bike's Best of 2007, Mountain Bike Magazine, November 2007, Rodale.

REFERENCES

1. Blumenthal T. IMBA Trail News, vol. 17(1). International Mountain Bike Association: Boulder, CO, 2004.
2. Redfield R, Sutela C. A bond graph model of a full-suspension mountain bicycle rear shock. Proceedings of the Engineering of Sport 6, International Sports Engineering Association (ISEA), vol. 1. Munich, Germany, 2006; 109–114.
3. Karnopp D, Margolis D, Rosenberg R. System Dynamics: Modeling and Simulation of Mechatronic Systems. John Wiley & Sons: New Jersey, 2006.
4. John J. Gas Dynamics. Allyn and Bacon: Boston, 1969.
5. Werner S, Newberry W, Fijan R, Winter M. Modeling of bicycle rider collision kinematics. Proceedings of the 2001 SAE World Congress; Warrendale, PA, 2001.

Received 2 January 2008
Revised 19 February 2008
Accepted 28 February 2008

Published online 18 September 2008