MULTICRITERIA OPTIMIZATION FOR THE REGULATION OF 
VEHICLE ANTI-LOCK BRAKE SYSTEMS

by

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ABSTRACT
Regulations for passenger vehicle anti-lock brake systems (ABS) exist in Europe, and are being actively considered in the United States. There is evidence that the safety related performance criteria compete with each other. One ABS system cannot be best in all categories, but instead trade-offs of desirable attributes must be made. This greatly increases the difficulty of framing sound ABS regulations. This paper discusses ABS performance regulation, suggesting that it should be grounded in the theory of stochastic multicriteria design optimization and should rely upon numerical simulation.

KEY WORDS: ABS control, optimal design, multicriteria, government regulation
INTRODUCTION

Computer assisted vehicle brake systems are commonly referred to as anti-lock brake systems (ABS). An anti-lock brake system makes adjustments to the fluid pressures that govern the four brakes on a vehicle. These adjustments modulate the outputs from the brakes to increase utilization of the available road-to-tire adhesion.

There is evidence that the anti-lock brake system (ABS) performance criteria that relate to vehicle safety compete with each other [Athan and Papalambros]. One ABS system cannot be best in all categories, but instead trade-offs between desirable attributes must be made. This agrees with intuition. A system that responds rapidly will tend to perform well at transitions in tire-to-road adhesion, but may be less robust to errors in sensor measurements. A system tuned to maximize steerability could not also minimize stopping distance.

This incompatibility of performance criteria greatly increases the difficulty of framing sound ABS regulations. The regulations should not be based upon the premise that a single and certain ideal system could be envisioned and used as a goal towards which regulations would herd manufacturers. While regulations could apply pressure upon manufacturers to improve their systems, some of the important performance attributes are inherently competing. Even if manufacturers could make perfectly, the determination of the proper performance criteria trade-offs would be difficult. Any regulation with stringency will influence how the trade-offs are made.

This argues against piecemeal promulgation of ABS performance regulations. Rule-making is never easy and so there may be a temptation to begin small, with a single regulation such as stopping efficiency. Yet such a design constraint could eliminate ABS systems that provide superior overall performance, while being relatively weak with respect to that one criterion. This concern encourages the recognition that this is a multicriteria design optimization problem. Regulation is closely related to design: regulation is the
determination of an allowable range of designs rather than the determination of one single design.

The first section of this paper considers the current activities in support of ABS regulation, and the near term possible outcomes. The second section considers ABS regulation in a long term perspective. Throughout this review the potential roles of multicriteria optimization and numerical simulation are discussed.

1 Current ABS Regulation Activities

Regulations for passenger vehicle anti-lock brake systems (ABS) exist in Europe, and are being actively considered in the United States. United States government regulatory agencies do not currently mandate the installation of ABS, nor impose requirements upon ABS performance, for vehicles weighting less than 10,000 lbs ("light vehicle"). A light vehicle equipped with ABS is required to meet the same stopping distance requirements as one without ABS. In March of this year ABS was mandated for vehicles weighing more than 10,000 lbs [The National Highway Traffic Safety Administration, 1995, FMVSS 105], and a single performance test was imposed.

The first subsection describes the current discussion led by the National Highway Traffic Safety Administration (NHTSA). The second subsection discusses the two most likely approaches to ABS certification in the near term: road test and hardware specifications. Subsection 1.3 considers certification using numerical simulation and multicriteria optimization. Subsection 1.4 discusses current uses for numerical simulation and simulation-based multicriteria optimization in ABS design and regulation.

1.1 Notice of Proposed Rulemaking

A NHTSA advanced notice of proposed rulemaking was published in January of 1994 [National Highway Traffic Safety Administration, 1994, Docket 93-94]. Rulemaking notices are issued to allow industry the opportunity for comment. The United States
Congress, in its Intermodal Surface Transportation Efficiency Act of 1991, directed NHTSA to issue this advanced notice of proposed rulemaking to consider the usefulness of additional ABS regulation. Congress also specified that this rulemaking action must be completed no later than January of 1997. The action will be considered completed when the agency either promulgates a final rule or decides against promulgating a rule.

The notice on ABS regulation is primarily a request to all interested parties for information and ideas pertinent to ABS regulation. Twenty-four questions are included. They ask for information on the expected costs and benefits of ABS technology, for information on the present and the anticipated future state of the technology, and for general and specific suggestions for ABS regulation.

The NHTSA asks if ABS should be made mandatory for light vehicles, and if so within what time frame. If made mandatory, the NHTSA asks how an ABS system should be defined. The NHTSA asks for suggestions for road tests: which surfaces and which maneuvers should be used, how should the input to the brake pedal be specified, and which performance metrics should be used.

Finally, The NHTSA asks for opinions about providing consumers with information that would help them decide between ABS technologies. The information could be based upon hardware categories, or upon one or more measures of road test performance.

1.2 Current Approaches in ABS Regulation

Currently regulators regulate either with road test requirements or with hardware requirements.

Road Tests

Both regulators and manufacturers generally prefer that regulations focus upon performance rather than upon hardware. Yet manufacturers have concerns about brake
REGULATIONS THAT REQUIRE ROAD TESTS BECAUSE MANY STOCHASTIC INFLUENCES AFFECT ROAD TEST PERFORMANCE. A MACHINE THAT WILL BE USED UNDER PSEUDOMORPHIC ACTUAL DRIVER INPUTS HAS NOT YET BEEN ACCEPTED ACROSS THE INDUSTRY. THE JOB OF DESIGNING SUCH A MACHINE IS DIFFICULT BECAUSE HUMAN BEHAVIOR IS A DYNAMIC OUTPUT FROM A SOPHISTICATED CLOSED-LOOP CONTROL SYSTEM. BRAKE FRICTION ELEMENTS ARE DIFFICULT TO CONTROL. MOST IMPORTANTLY, TIRE-TO-ROAD ADHESION IS DIFFICULT TO CONTROL.

IF ROAD TEST CERTIFICATION IS REQUIRED, MANUFACTURERS WILL CONDUCT THE TESTS AND WILL BE RESPONSIBLE FOR MAINTAINING APPROPRIATE TEST SURFACES. A ROAD TEST WITH A SURFACE ADHESION SPECIFIED BY A TEST TIRE SKID NUMBER WAS RULED IMPrACTICABLE BY A FEDERAL COURT [PACCAR, 1978]. THIS RULING INVALIDATED A HEAVY VEHICLE BRAKE TEST REGULATION, AND IT HAS IMPLICATIONS FOR ALL BRAKE TESTING INVOLVING ROAD ADHESION SPECIFICATION.

A THOROUGH MULTICRITERIA ASSESSMENT OF AN ABS SYSTEM WOULD INVOLVE PERFORMANCE CRITERIA MEASUREMENTS OVER A GREAT MANY COMBINATIONS OF STOCHASTIC PARAMETERS FROM THEIR FULL RANGES. FOR EXAMPLE, RATHER THAN INCLUDING TWO SEPARATE BRAKING EFFICIENCY CRITERIA, ONE ON WET PAVEMENT AND ONE ON DRY, A SINGLE BRAKING EFFICIENCY CRITERION WOULD BE USED, EVALUATED OVER THE FULL RANGE OF ACTUAL ROADS. THIS PROVIDES A MORE RELISTIC ASSESSMENT OF ACTUAL CUSTOMER USE, AND GREATER INSIGHT INTO PERFORMANCE.

A RELIANCE UPON ROAD TESTS WOULD CONSTRAIN THIS EFFORT. PRACTICABILITY WOULD IMPOSE A LIMIT TO THE NUMBER OF TESTS, PRECLUDING A REALISTIC APPROXIMATION TO THE EXPECTED RANGES OF THE STOCHASTIC PARAMETERS. IT MAY BE DIFFICULT ANALYTICALLY TO COMBINE A LIMITED SET OF TEST RESULTS TO ENABLE A SEPARATION BETWEEN STOCHASTIC INFLUENCES AND PERFORMANCE CRITERIA. THIS DIFFICULTY WILL MAKE MULTICRITERIA ANALYSIS OF RESULTS MORE DIFFICULT. RESULTS WILL LIKELY BE TOO FRAGMENTARY TO GENERATE BROAD COMPREHENSION OF SYSTEM CAPABILITIES.

PERFORMANCE REGULATIONS SHOULD BE BASED UPON KNOWLEDGE OF THE ULTIMATE LIMITS OF ABS CAPABILITIES. THE NHTSA WOULD PROBABLY DEVELOP A SENSE OF THESE LIMITS FROM NEGOTIATIONS WITH THE MANUFACTURERS OVER PRACTICABLE PERFORMANCE REQUIREMENTS. YET SUCH INFORMATION EXCHANGE WILL NOT BE PERFECT, FOR THE PARTIES ARE NOT DISINTERESTED.

Hardware Specification
The original guidelines for the NHTSA specified that standards should be stated in terms of performance rather than design, specifying the required minimum level of performance but not the manner in which it is to be achieved [U.S. Department of Commerce, 1967]. In practice, a narrowly defined performance requirement could effectively specify hardware.

A hardware requirement, such as mandatory implementation of ABS technology, requires a thorough specification of hardware so that use of inadequate hardware is prohibited. A thorough specification, however, can restrict technology development. This is of particular concern when the technology is not yet mature, as is the case for ABS. The specification would act as a set of artificial design constraints.

The specification would therefore probably be formulated to allow a range of design solutions. The consumer would probably not be able to discriminate between these systems, and therefore there would be little incentive for a manufacturer to make improvements.

The NHTSA probably could not even ensure that all hardware that met the specifications would provide improved performance over the performance of brake systems without ABS. Even the best ABS systems will degrade some performance capabilities for the average driver (for example, stopping distance on loose snow and on gravel is often made worse by ABS operation). Rear wheel only ABS often increases stopping distances, but increases directional control [Hiltner et al., 1991]. A highly skilled driver can outperform the best ABS [Hiltner et al., op. cit.]. Because the NHTSA cannot specify that all capabilities must be greater with than without ABS, a contentious multicriteria optimization debate might result from efforts to specify which capabilities can be degraded and which cannot. Moreover, to do so means reliance upon road tests.

Whether the NHTSA specifies performance requirements for certification or instead requests that manufacturers use a rating system to educate consumers on the relative merits
of ABS systems is largely a question of regulatory philosophy. The considerations over road tests and over hardware specification that were discussed in this subsection apply to either approach.

1.3 Computer Simulation for ABS Certification

Given the concerns over both hardware specification and road test certification, a certification that relied upon computer simulation would appear attractive. In simulation, stochastic parameters can be represented in a numerical approximation technique such as Monte Carlo simulation. It is probable that every manufacturer currently uses computer simulations to some extent for brake system design, though the degree of sophistication may vary among them.

Yet there is little likelihood that computer simulations will be used for certification in the near future. The stochastic parameters are difficult to model. To assess brake lining friction performance throughout a stop a sophisticated thermal model would be required. The simulation of driver performance is difficult, as are simulations of tire adhesion and deformation. These difficult to model components are critical to ABS performance. Computer simulation has not yet been used for any brake system certification.

Even if a manufacturer made the substantial commitment to develop a simulation adequate for certification, the manufacturer may have little incentive to share that technology with the NHTSA and with all other manufacturers. In support of rulemaking, manufacturers have at times shared substantial amounts of proprietary information in the belief that the loss would be offset by the benefits of an improved regulatory procedure.

It is not necessary for all manufacturers to use the same simulation for developing their ABS technology. In a test case, the court determined that the standard of reasonable care, which is applied in many other negligence situations, should be applied to vehicle safety [Larsen vs. General Motors Corporation, 1968]. Yet certification requirements must be equivalent for all manufacturers, and this would appear to mandate use of one simulation
by all. This approach is analogous to current certification in which all manufacturers must conduct the same certification road tests, while they may differ in the developmental tests that they rely upon.

Even if a manufacturer developed the simulation and was willing to share it, the NHTSA and the other manufacturers would have to be convinced of its reliability. Considerable test validation would be required to develop this assurance. There would be periods for industry review and comment, changes would be proposed, and years would likely pass in the process.

Nonetheless certification through simulation would hold great benefits for ABS regulation. Perhaps in this era of greater cooperation between industry and government a joint effort could be made to develop a simulation for ABS certification. It has been argued that the U.S. government underfunds traffic safety relative to its funding of other health programs. For every year of productive life lost due to a highway fatality the government research investment was $27 in 1987. For cardiovascular disease research the amount was $297, and for cancer research the investment was $587 [Digges, 1987].

1.4 Current uses of Computer Simulation and Optimization for ABS

Though it may be some time before computer simulation is used for ABS certification, it can in the meantime impact ABS design, and even ABS rulemaking.

*Simulation-based Optimization for ABS Design*

For a simulation to be adequate for certification its outputs must closely match actual vehicle performance. The simulation must indicate whether actual vehicles will perform as required.

A simulation for design purposes need not be as accurate. If it captures performance trends it can direct the decision maker to an optimal solution. Some manufacturers may already be relying upon simulation-based numerical optimization for
ABS design, while undoubtedly others still rely upon vehicle test, using optimization in an occasional fashion for insights into system performance. Because of the great advantages, it can be expected that all manufacturers will increasingly rely upon optimization in their design work. Simulation can be used to select between the many approaches to nonlinear control algorithm design, and can be used to optimize the selected approach. It can also be used to evaluate changes to system hardware, such as in actuator rates and in sample rate.

For most manufacturers at this time, it is assumed that multicriteria methods could be used to generate ideas to be evaluated in road tests, and to help understand results from road tests. The focus remains upon road tests, not simulation.

Simulation-Based Optimization for ABS Rulemaking

Though simulation may not soon be used for ABS certification, it can play a role in ABS certification rulemaking. If the NHTSA goes forth with the intention to promulgate road tests for certification, the information that can be provided with simulation-based optimization can be important in the formulation of the requirements. Multicriteria optimization can deliver a representative assessment of the capabilities of one or more ABS strategies. This can help the NHTSA set practicable performance requirement levels. Regulations should be based upon knowledge of the criteria trade-offs.

Multicriteria optimization can also be useful if the NHTSA mandates ABS. Design studies to evaluate hardware implications can assist in the definition of the essential requirements for adequate ABS hardware. For example, performance of an optimized three actuator system (one actuator serving both rear brakes) could be compared to performance for an optimized four actuator system. If the difference is great, a regulation requiring one actuator for each brake might be supported.

In all such studies the quantitative results may be of uncertain accuracy, but the qualitative conclusions can alert the NHTSA to potential problems that should be prevented by regulation.
An approach that has proven useful in manufacturer responses to notices of proposed rulemaking is to define a representative vehicle and perform calculations for it to derive conclusions about the practicability of proposed rules. The calculations are generally made analytically and therefore can be verified by the NHTSA and by other interested parties. It is unclear whether this approach can be extended to ABS rulemaking.

The calculations required to demonstrate a result of interest to ABS rulemaking are much more extensive, yet must be explicit if their results are to be believed. Even then, they will rest upon assumptions that may require considerable vehicle test validation before acceptance.

Also, the ABS algorithms in use are proprietary and the manufacturer would not wish to relinquish the competitive advantages that they provide. This restricted access makes a realistic simulation of ABS performance difficult. As mentioned above, manufacturers have at times released proprietary information in the belief that the loss would be more than offset by the benefits to the resulting regulations. Yet algorithms can be very expensive to develop, and their advantages are long lasting because their confidentiality can be more easily maintained than can the confidentiality of hardware technology, which can be directly copied. An alternative would be to use in the demonstrations only those ABS control algorithms that have been published.

These considerations again lend support to the arguments for a coordinated effort between manufacturers and the NHTSA. At present there is minimal competitive advantage to be derived from ABS algorithm development. Differences in capabilities between algorithms, even if significant, are too difficult for the consumer to perceive. Perhaps this will encourage manufacturers to share ABS algorithm development. Also, shared development would probably reduce the liability vulnerability of each manufacturer. Shared development would reduce each manufacturer's development costs, too.
Shared development might not benefit everyone. Suppliers have undertaken substantial development efforts. Some vehicle manufacturers have both their own ABS algorithm development and purchase agreements with ABS suppliers. The suppliers may have reason to fear loss of business once their proprietary information has been shared.

There could initially be difficulties in cooperation because of the differences among vehicles and among ABS hardware. Ultimately, however, some industry-wide standardization for ABS systems would probably result.

2 The Future of Multicriteria Optimization for ABS Regulation

For the present, most manufacturers will probably place simulation-based optimization of ABS technology in a support role, largely conducted in an ad hoc fashion. Simulation-based optimization has become central to many aspects of vehicle design, but ABS technology poses exceptionally difficult challenges for simulation.

Insights gained from optimization will be useful to design and to rulemaking. Because the benefits of greater reliance upon optimization are obvious and substantial, such reliance can be expected to increase steadily over time. Each successful optimization effort will help to develop greater trust in numerical methods.

This section examines the possibilities for a larger role of numerical simulation and simulation-based optimized sometime in the future. The assumption is made that the NHTSA and the manufacturers share an accurate vehicle ABS simulation, just as they now share road test equipment that at one time provided competitive advantage to one or more manufacturers.

2.1 Rulemaking and Certification

The existence of an accepted ABS simulation for ABS performance evaluation would have many benefits. The NHTSA could evaluate the manufacturers' ABS algorithms in a
completely confidential "black box" fashion. This evaluation would enable the determination of practicable performance requirements.

Manufacturers could certify their vehicles through simulation. Hardware tests would be required to assess component characteristics for the simulation, but this information would be routinely developed in the component design process. This would deliver greatly reduced certification costs.

The simulation would provide encouragement to the development of better ABS systems, for it would allow a clear validation of improvements. An ABS supplier could promote an ABS system with the results from the government simulation.

Certification could use "hardware in the loop" simulation of the ABS system, in which the actual electronic control circuitry and actuators are connected into a simulation. Tire and road characteristics and perhaps brake characteristics too would be simulated in "real time."

By encouraging market force influence upon ABS development, the existence of an accepted ABS simulation may make ABS requirements unnecessary. Government regulators would continue to play a role, but the role would be in the decision making required to formulate the simulation, as described in the following subsection.

2.2 Decision Maker Involvement

The use of numerical simulation and multicriteria optimization methods does not eliminate the reliance upon decision makers for design and rulemaking decisions. Instead, it provides a framework for the decision making, encouraging explicit and quantified justifications for the decisions. If numerical optimization methods become an important part of certification, difficult decisions will have to be made in two areas: In constructing the simulation, decisions will have to be made about the proper mix of stochastic influences used in assessing ABS performance; In evaluating the results, decisions will have to be
made about the relative importance of the performance criteria. These two sets of decisions are discussed in the two subsections below.

Lowrance [1976] has suggested that the topic of risk assessment should be divided into two distinct categories. There is the measurement of risk, an essentially objective and scientific activity. There is also judgment of safety, which is a normative and political activity. As will be described in this subsection, there is considerable uncertainty in both of these categories. In the following discussion it appears that Lowrance's two categories are intertwined. Safety judgments must be made to determine the approach to the measurement of risk.

Uncertainty has always existed in vehicle brake development decisions. Because certainties are unavailable, there may be a range of justifiable solutions. Each justification may depend upon a different interpretation of the uncertainties. This uncertainty has placed a focus upon insisting that the procedures for making decisions are correct rather than insisting that the solutions are indisputable [Council for Science and Society, 1977]. This focus encourages the development and use of quantitative multicriteria decision methods.

Decisions Made about the Simulation Formulation
The construction of the simulation will require decision maker inputs. In particular, the determination of the proper representation of stochastic influences will be difficult. For example, this would include the determination of the relative importance of different vehicle speeds, different road characteristics and different vehicle loadings. The determination of how stochastic influences should be represented in the official simulation would be expected to have a large impact upon the simulation’s evaluations of ABS system performance.

If decision makers rely upon accident data for determining the relative importance of the stochastic parameters there would be reasons for using recent data. Vehicle characteristics change and this could impact the demands placed upon ABS systems. Yet
because ABS implementation will be high it may be difficult to remove the influence of earlier ABS hardware upon the statistics to extract the essential requirements.

Also, driver behavior may change over time. What is considered excessive risk may vary over time, varying with the ethics of the community and the nation [Baker, 1971]. Some drivers are risk seeking [Klein and Waller, 1970].

One model of driver behavior, the risk homeostasis model [Blomquist, 1988], believes that drivers are comfortable with a specific level of risk, and they adjust their behavior to maintain this level. This approach would suggest that, for example, a new safety technology such as air bags would, by reducing driver risk, lead to riskier driving. This riskier driving would alter the demands upon the ABS system. If all drivers acted entirely in accord with this model there would be no safety benefits from safety technology. Policy should then be directed at changing the acceptable level of risk.

While this model has been strongly criticized [Evans, 1994], it is clear that the introduction of safety technologies can result in changes in the behavior of drivers. As a result the net safety impact upon driving populations may differ substantially from what would be expected from objective test track performance changes. This phenomenon is the probable explanation for the many recent surprises in the data from widespread ABS use [Highway Loss Data Institute, 1994, 1995; National Highway Traffic Safety Administration, 1994, Technical Report]. Evans reviews a number of safety technologies and finds that some have greater impact than expected, some less, and some in the opposite direction from what had been expected, due to resultant changes in driver behavior [Evans, op cit.].

Complicating the assessment of driver behavior changes are the different attitudes to risk throughout the population [Peltzman, 1976]. If, for example, young adults maintain a higher level of risk than do older adults, the pattern of deployment of a new safety technology will influence the trends in driver behavior. If a safety feature first appears only on more expensive models, which are largely the province of older drivers, then the change
in driving behavior due to the feature may initially be small. This influence would be expected to change as the technology is implemented on less expensive vehicles. Yet if the technology roll-out takes a number of years, the trend due to different attitudes to risk between age groups that was just described may contend with a trend that results from the different attitudes to risk between generations (e.g., one set of young adults may have a different attitude toward risk than the following generation of young adults does). Further complications arise from the influence of income upon risk aversion, and from the influence of vehicle age upon accident reporting. Also there is evidence that driver age influences accident reporting rates [Klein and Waller, 1970].

There will always be uncertainty in the determination of the relative importance of the stochastic influences. Agreement has not been reached among experts over the proper model for driver risk, and that is only the first step in risk assessment. Also the data that are relevant to the decisions are not available. For example, there may be a correlation between the number of vehicle occupants and the likelihood of an accident that an ABS system could prevent [Klein and Waller, 1970]. This information is not available, because although accident records do include the number of vehicle occupants the number of occupants in accident-free vehicles is not known.

Yet another uncertainty in evaluating accident trends results from the changing road environment. For example, there has been a sizable effort to upgrade road surfaces to materials that are better for wet weather brake performance [Solomon, 1988].

Because of the large uncertainties, decision makers will have large latitude in their solutions. The influence that this latitude will have upon the development of regulations is unclear, because the placement of the burden of proof has not been established [Tarlock, 1976]. Because many conclusions relevant to ABS cannot be proven, if a traditional burden of proof is placed upon regulators, there will be little regulatory activity. If the burden of proof is placed upon the opponents of regulation, regulations will be very difficult to prevent. An intermediate notion of the burden of proof may be worthwhile.
[Tarlock, op. cit.], and it could be defined by legislation. There is no burden of proof for legislative acts [Clarkson, 1976].

**Decisions Made about the Criteria Trade-Offs**

Vehicle rulemaking has generally tried to focus upon a single criterion: cost. The second and most essential criterion, safety, is converted to cost. This conversion enables cost-benefit analysis for a new regulation. In 1971 the NHTSA approximated each life saved as worth $200,000 and each injury avoided as worth $6000 [NHTSA, 1972]. These approximations have been periodically updated. It was based upon the expected losses in earnings. Other approaches have been used, with quite different resulting estimates. There is a trend in U.S. governmental cost-benefit analyses to use willingness-to-pay estimates instead of losses in earnings [Scodari and Fisher, 1988]. Willingness-to-pay uses an estimate of the dollar value that drivers place on their lives. This number is difficult to assess.

The cost-benefit analyses that have been used in debates over regulation have generally been controversial. The NHTSA and the manufactures generally diverge in their estimates of the cost of hardware development and hardware production. The safety benefits, too, are difficult to assess. As described above, this difficulty is due in part to changes in vehicles and their operating environments, and changes in driver behavior.

Along with an assessment of the the ABS performance criteria that relate to passenger safety there may be bound up some other performance criteria. Should regulators consider passenger comfort? Change in the rate of vehicle deceleration is an ABS performance criterion that relates to passenger comfort. Comfort will play an increasingly important role as active suspension technology is implemented, for one of its chief benefits is passenger comfort, while it can also have an impact upon braking performance. Should active suspension design ignore passenger comfort during a maximum deceleration stop?
The historical cost benefit analysis that converted the safety criterion to cost to enable a single criterion analysis often ignored considerations of equity [Miller, 1988]. Some population groups bear the costs of a regulation while others receive the benefits [Taylor, 1988]. For example it has been suggested that the introduction of seat belts was bad for pedestrians: seatbelts led to riskier driving [Peltzman, 1976]. Thus even if safety can be converted to cost, the problem involves multiple criteria (e.g., cost-benefit to pedestrians vs. cost-benefits to drivers).

While determination of the proper criteria trade-offs may never be settled, reliable simulation-based multicriteria optimization can be used to ensure that only Pareto Optimal trade-offs of the criteria are used. (A criteria vector solution is Pareto Optimal if it is as good as all other solutions with respect to each criterion and better with respect to at least one. If preferences are monotonic with respect to all criteria then only Pareto Optimal solutions are rational choices.)

This subsection summarizes a daunting list of challenges in the development of a certification simulation. There will never be perfect solutions to those challenges, but it is conjectured that reasonable and practical solutions would provide a simulation that would be a large improvement over current methods.

3 Concluding Remarks

In the future, both customers and regulators will expect a well-designed passenger safety capability. The producers of ABS will be required to convince customers and regulators that their ABS design methodology delivers desirable designs. Multicriteria design optimization methods are well suited to this task.

Numerical optimization methods feature an explicit and quantified design process. In this they offer an important advantage over the traditional heuristic design process. Because ABS performance has safety implications its design will receive public scrutiny.
Antilock brakes gave rise to serious product liability suits soon after being introduced into the trucking industry in the 1960s and 1970s [Syverud, 1992]. Recent cases in the United States indicate that jurors have difficulty following the technical explanations of how an antilock braking system is designed and how it works [Syverud, op. cit.]. The use of numerical optimization methods will make the design process more easily understood by those not directly involved in it.

Multicriteria optimization methods do not eliminate decision maker judgment from the design process. Instead, they provide a quantitative framework for the decision maker's judgment. The decision making methodology is very important for ABS technology development because there is so much uncertainty in the relevant data bases.

The U. S. government is now formulating its role in ABS technology development and deployment. The discussion in this paper encourages the development of a thorough and clearly articulated framework for ABS development and deployment, as contrasted with a piecemeal approach. The initial costs may be high because construction of the framework would be a sizable undertaking, but those costs would be more than offset by savings over time.

ACKNOWLEDGMENT

As in our other papers,

REFERENCES

Your thesis should be prominently referenced in the introduction as motivation for this article (or vice versa...).