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# Standards and Innovation:
# U.S. Public/Private Partnerships to Support Technology-Based Economic Growth*

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ABSTRACT: This paper examines how strategic alliances to create and use standards affect economic growth and development. The explanation of the link from standards to economic growth and development is through the effects of standards on the incentives to perform industrial research and development (R&D). We examine product standards, metrology traceable to national and international standards, and regulatory standards to address negative externalities. The paper develops a theoretical explanation for the link from standards to growth, survey/interview-guides to gather information from industrial R&D experts about the explanation, and case-study evidence about the explanation. We discuss the standard-setting process and explain it entails strategic alliances among firms and with government involvement. Case studies of R&D projects in firms and in a national laboratory support the belief that standards implemented via strategic alliances leverage economic growth and development.

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KEYWORDS: standards, innovation, standard-setting organizations (SSOs), research and development (R&D), national laboratories, Corporate Average Fuel Economy (CAFE) fleet average standards

JEL CLASSIFICATIONS: O31, O32, O33, O34, O38, L510, L62, L63

## I. Introduction

This paper introduces a new approach to evaluating research and development (R&D) investments and applies the approach in 14 case studies to examine how strategic alliances to create and use standards affect economic growth and development. The use of standards in industry entails strategic alliances of various forms, and we examine the effects of those alliances that promulgate product standards, metrology traceable to national and international standards, and regulatory standards to address negative externalities. We describe the standard-setting process as a strategic alliance not only among firms but also with government involvement.

Our explanation of the link from standards to economic growth and development is through the effects of standards on the incentives to perform industrial R&D.[1] Our case studies juxtapose the opinions of industrial experts with the theory of investment in R&D to provide evidence that standards implemented via strategic alliances—firms receiving the support of standard-setting organizations (SSOs) and national laboratories, and also the alliance of government, labor, consumers, and firms to implement regulatory standards—do leverage economic growth and development. Moreover, we explain and illustrate how net social value would be increased with additional public funding for a prominent public/private partnership to develop socially valuable technology for the automobile industry.

The range of important product and measurement standards is wide, including standards for the physical characteristics of products (e.g., interoperability as with USB ports, or safety as with building materials) and services (e.g., communications as with protocols allowing exchange of data in high-speed communications networks, or security as with health records) and standards for measurement (e.g., thermocouple calibration for accurate measurement of temperature, traceable to a national or international standard).

For product standards, firms depend on the capabilities of SSOs and other industry organizations that form strategic alliances among firms to ensure that each firm can compete successfully with its proprietary products that must be compatible with the products supplied by other firms. The activities of SSOs often draw on expertise at government laboratories; hence,

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[1] Standards, in contrast to nominally stronger intellectual property protection which increases R&D incentives while reducing the available pool of knowledge (Stiglitz, 2014), may increase incentives as they expand the relevant pool of knowledge and make it more accessible. See Section V.

the process of setting standards and using them in commerce entails a strategic alliance in a public/private partnership.[2]

Support from government laboratories for the activities of SSOs and industry more generally often centers on measurement and calibration protocols (i.e. metrology) that are traceable to national and international standards maintained at a national laboratory. Industrial users of traceable measurement standards have productivity-enhancing access to the capabilities of the national laboratory. Development and application in industry of useful measurement standards often requires collaborative effort between industry and government laboratories to ensure that the measurement needs of industry are understood and the appropriate measurement standards and procedure for applying them and providing traceability are developed.[3]

In addition to product and measurement standards, there are also standards that address social concerns about effects of market processes when the costs are not faced fully by the participants in the market. We examine a prominent example of such standards—the new CAFE standards[4], announced August 28, 2012, mandating for the U.S. auto fleet an average fuel economy of 54.5 miles per gallon by 2025.[5] The CAFE standards address social concerns about energy and the environment.[6]

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[2] Leyden and Link (1999) explain that in addition to providing technical support, government laboratories can serve the role of an honest broker to facilitate agreement among firms.

[3] See Tassey (1997), Link and Tassey (1987), and Link and Scott (2013).

[4] These new standards are the Corporate Average Fuel Economy (CAFE) fleet average standards for 2025.

[5] An important question is whether the new mandate has "teeth"—i.e., is accompanied with a credible threat of a sufficiently substantial penalty to "bite" when a company does not meet the standards. The answer is yes, according to a knowledgeable senior Department of Transportation (DOT) official with whom we spoke. Under the old CAFE standards, it was just a matter of fuel economy and everything was handled by DOT. Then, as now, monetary penalties depended on an average miles per gallon short of meeting the standards. There is a penalty if on average the corporation misses the target, and at times companies have opted to pay that fine and give customers the larger, more powerful (and hence less fuel efficient) cars they want (given relatively low gasoline prices). Companies also shifted emphasis toward "light trucks" including "sports utility vehicles" (SUVs) for which the old CAFE standards were less demanding. Now, with the new CAFE standards, EPA is on board, and given its authority under the Clean Air Act, if requirements are not met, a company could actually be forced to cease production. With DOT alone, the company could produce when failing to meet standards, but would have to pay a penalty. With the new standards that are jointly enforced by DOT and EPA, companies that do not meet the standards cannot simply count on paying a fine and continuing operations. However, as one expert (who has over many decades studied the automobile industry, industry quite generally, and government policies toward industry) told us, "A threat to shut down a whole production operation is simply not a credible threat in our political economy." The effectiveness of non-compliance penalties is an open question, and

> Following the direction set by President Obama on May 21, 2010, NHTSA and EPA have issued joint Final Rules for Corporate Average Fuel Economy and Greenhouse Gas emissions regulations for model years 2017 and beyond, that will help address our country's dependence on imported oil, save consumers money at the pump, and reduce emissions of greenhouse gases that contribute to global climate change. (http://www.nhtsa.gov/fuel-economy)

Development of the new CAFE standards involved collaboration between industry and government. The standards followed the agreement, announced on July 29, 2011, between the Obama administration and automobile manufacturers, to increase mileage standards and cut greenhouse gas emissions for new cars. The official press release on August 28, 2012 of the U.S. Department of Transportation (DOT) and the U.S. Environmental Protection Agency (EPA) emphasized the belief that the new standards will encourage investment in innovation and generate economic growth and development. The announcement also emphasized that the new standards reflect the interaction of industry, consumer groups and the government. The August 28, 2012, press release "Obama Administration Finalizes Historic 54.5 mpg Fuel Efficiency Standards" stated (http://www.nhtsa.gov/fuel-economy):

> Achieving the new fuel efficiency standards will encourage innovation and investment in advanced technologies that increase our economic competitiveness and support high-quality domestic jobs in the auto industry. The final standards were developed by DOT's National Highway Traffic Safety Administration (NHTSA) and EPA following extensive engagement with automakers, the United Auto Workers, consumer groups, environmental and energy experts, states, and the public. Last year, 13 major automakers, which together account for more than 90 percent of all vehicles sold in the United States, announced their support for the new standards. By aligning Federal and state requirements and providing manufacturers with long-term regulatory certainty and compliance flexibility, the standards encourage investments in clean, innovative technologies that will benefit families, promote U.S. leadership in the automotive sector, and curb pollution.

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the simulation in this paper of our model of R&D investment and performance is one approach to understanding what the actual effects of the new standards will be.

[6] The evidence suggests that any "rebound effect" from drivers choosing to drive more miles (when the cost of driving each mile falls because of increased fuel efficiency) does not completely offset the reduction in fuel consumption achieved by the new technology (Greening, et al., 2000; Kotchen, 2012). The CAFE rulemaking information and documents are available at http://www.nhtsa.gov/fuel-economy. The site provides the key documents with detailed information about the final rule and the joint efforts of the Department of Transportation (DOT) and the Environmental Protection Agency (EPA).

Crandall et al. (1986) and White (1982) provide landmark studies of regulatory standards applied to the automobile industry. To have these important studies as a benchmark to which our approach and findings can be compared (and also to have an application of great interest), we use the automobile industry for our regulatory standards example. Crandall et al. (1986) examine three types of regulatory standards that have been applied to the automobile industry—safety standards, emissions standards, and fuel economy standards. The fuel economy standards they examine are the original CAFE standards introduced in 1975 when the initial fuel-efficiency goal was 27.5 miles per gallon by 1985, essentially half the new CAFE standard to be achieved by 2025.

Crandall et al. (1986, p. 4) observe:

> Obviously, each statute requiring federal regulation of the automobile is designed to force automobile manufacturers to provide some attribute—emissions control, safety, or fuel economy—to a greater degree than the market would dictate. . . . An obvious question to ask for each program is whether regulation has succeeded in reducing the undesired by-product or externality that it addresses.

White (1982, pp. 8-10) provides a full discussion, in the context of the regulation of automobile emissions, of the economics of a negative externality and appropriate regulatory policy. The political process has developed the direct, regulatory approach to controlling automobile emissions, but White (1982, pp. 92-97) explains the efficiency and flexibility of an effluent fee system to better align private decisions with the social welfare by internalizing external costs caused by driving automobiles. In addition to the emissions externality, there is a pecuniary externality that can be addressed with regulation. Scherer (1996, pp. 326-327) explains that consumers' propensity to prefer larger cars, other things—in particular the price of gasoline—being the same,

> . . . poses problems for government officials who advocate energy conservation in a wealthy nation like the United States. If consumer preferences are to be overridden, there must be some justification in a market failure. … [Consuming a large proportion] of the world's petroleum products, the United States has a significant impact on the price of crude oil. There is a pecuniary externality to U.S. consumption decisions. … [The CAFE standards] can be interpreted as a second-best solution to the crude oil price externality problem imposed in lieu of the first-best monopsony taxation solution.

Fuel economy (measured in miles per gallon) and reduced emissions (measured in amounts of a substance emitted per mile) tend to move together, although not always in lockstep. For example, White (1982, pp. 60-64) describes the increased fuel consumption resulting from an early generation of emissions controls needed to meet the emissions standards in the late 1970s. The controls were estimated to increase fuel consumption by about 3 percent. Earlier in the 1970s, before the mid-1970s introduction of oxidizing catalysts and unleaded gasoline, the controls (which had required engine modifications to reduce CO and HC emissions, combined with exhaust gas recirculation to control $NO_x$) resulted in the fuel economy penalty being much higher. White provides estimates of the reduction in fuel economy resulting from meeting the standards for various years throughout the 1970s and early 1980s.

Although the CAFE standards are a government regulation, their success will require a collaborative strategic alliance of industry and government with forthright sharing of information about technological and organizational constraints. Moreover, as discussed subsequently, a prominent U.S. public/private partnership is doing collaborative research to develop the materials and processes needed for lighter-weight and hence more fuel-efficient automobiles to meet the new standards.

We gather information from industry and develop 14 case studies.[7] Mansfield et al. (1977, p. 222) explain that to find the respondents for the 17 case studies in their seminal paper about the innovations from industrial research, many companies had to be contacted because the sensitive nature of information about R&D investments led to a low response rate. Their resulting sample, they explain, could not be considered a random sample, although they had no reason to expect systematic bias that would affect their conclusions. Similarly, we had to contact many potential respondents to obtain our 14 case studies, and while our sample cannot be considered random, we do not expect the views of our respondents to differ systematically from those of the set of potential respondents.

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[7] Our theoretical model develops the work in Scott (2009) and Scott and Scott (2014) to allow a version of the model that is normalized in two dimensions to facilitate discussion of the relationships in the model with industry respondents; our theoretical development allows the reconciliation of the two normalizations. Our survey/interview-guide for product and measurement standards is in our working paper (Scott and Scott, 2013). Our survey/interview-guide for the examination of the impacts of the CAFE standards is described herein and uses the same new theoretical developments with the normalizations of key relationships, and allows us to discuss with industrial respondents the impact on R&D of the new CAFE mandate for fuel efficiency.

Our paper will explain how standards (product standards developed by SSOs and other industry associations and with the support of national laboratories, measurement standards traceable to a national laboratory and developed with collaboration of government and industry, and collaborative regulatory standards) can create incentives to increase industrial R&D and bring about economic growth and development. All three types of standards entail collaboration of industry and government. The survey approach we develop allows us to use the opinions of industrial R&D experts in case studies to calibrate the theoretical explanation of the R&D impact of standards and then simulate the effects of the standards on innovative activity.[8]

The remainder of the paper is organized as follows. Section II presents our model, and Section III explains the calibration of the model with our survey data. Sections IV and V use our case studies to evaluate the economic impact of product and measurement standards supported by strategic partnerships connecting firms, SSOs, and public laboratories. Section VI uses the example of the new CAFE standards to illustrate the impact of regulatory standards. Section VII concludes with discussion of the importance of strategic partnerships for effective standards that promote growth and development and also with discussion of our approach to evaluating the impacts of standards.

## II. The Model

Our formal model develops the model in Scott (2009) and Scott and Scott (2014) in appropriate ways to allow its simulation using information gathered from respondents in industry.

At the center of the model is an index $x$ of the *relative* quality of a company's technology (*relative* to the technology of its competition in the post-innovation market). The

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[8] In addition to illustrating the effects of standards on respondents' R&D investment and their expected net benefits from that investment, the examples of economic growth and development can be quite direct and occur rapidly. For example, one respondent describes the CAFE-standards-induced R&D to develop a lower-cost way to produce carbon fiber for automobile parts that "light-weight" cars and improve their fuel efficiency. The respondent's success—just two years from the agreement between the industry and the administration and a year after the announcement of the new standards—had won a contract to provide carbon-fiber parts for the next model of an expensive, relatively low production volume, high-performance car. The new contract supported the opening of a new plant to produce the contracted components. The ultimate goal of such CAFE-standards-induced R&D is to make cost-effective the use of new light-weight materials in high-volume mass-produced vehicles. As the R&D investments yield new sources of light-weighting materials and lower-cost ways of producing the final products, economic growth and development follow.

index is normalized so that $x = 100$ corresponds to a situation where the quality of the respondent company's technology is equal to that of its most successful rival. Uncertainty of the technical success of both the respondent's and rivals' research efforts is reflected by the distribution over values of $x$.

The probability density function $f(x)$ depends on the respondent's R&D effort $R_i$ and the research effort of rivals, denoted by $R_{-i}$. More research effort for a firm will shift its distribution rightward over higher values for $x$; more research effort by the firm's rivals will shift its distribution leftward over lower values for $x$.

In the post-innovation market, the higher the responding firm's relative quality, the more competitive it is and the higher the value—the present value of the stream of future profits in the post-innovation market—$V(x)$. We denote the present expected value of the innovation's future profits, which is $\int V(x)f(x;R_i)dx$, by $G(R_i)$.

The firm chooses its research effort to maximize expected net present value—the present expected value of profits in the post-innovation market net of the cost of research effort, $wR_i$, where $w$ is the unit cost of research effort:[9]

$$\max_{R_i}\left(G(R_i) - wR_i \equiv \int V(x)f(x;R_i)dx - wR_i\right)$$

Net present value, NPV, is maximized when the marginal cost of R&D equals the marginal expected value of future profits: $w = dG/dR_i$. This first-order condition is depicted in Figure 1 by the diagram showing the iso-NPV line tangent to the expected value function at the optimal level of R&D effort.

**FIGURE 1 ABOUT HERE**

In our case studies, we calibrate our model using survey data and then use the calibrated model to describe the R&D impacts of standards in innovative industries.

## III. Calibrating the Model with Survey Data

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[9] In a theory setting, *w* could be normalized at 1, effectively omitting it from the model, as it is in Scott (2009). When using survey data to calibrate the model, *w* is used to reconcile two normalizations—of R&D effort and the value expected in the post-innovation market—that are necessary to avoid questions about dollar figures. The details can be found in the Appendix.

Our survey begins by asking the responding firm for a description of its research and the standards used—standards for the attributes of products and services as well as standards for measurement.[10] In the case study that we present in detail to illustrate and explain our approach, the respondent, a senior R&D manager and researcher with one of the world's preeminent research-intensive firms reports:

> [The company] works in a huge variety of industrial research areas. The following answers to the survey are based on my small portion of [the company's] R&D. My area of industrial research is related to the supply of new and innovative materials for the manufacture of printed wiring boards. This includes flexible copper clad laminate substrates, coverlay and bondply materials, photoimageing materials, and high performance insulating films.

The respondent explains the technology standards most relevant to the company's research as follows.

> Technology standards that are most relevant to our research efforts are developed by industry associations such as IPC Association Connecting Electronic Industries, SMTA (Surface Mount Technology Association), IEEE and others related to electronics manufacturing. These standards cover a variety of areas including printed wiring board materials, printed wiring board manufacturing, assembly and quality.

The company uses measurement standards entailed in high frequency signal test methods for printed wiring boards and the standards used to calibrate precision instruments. The firm is engaged in creating new and improved photoimageable photoresists for creating printed wiring board circuitry, new and improved flexible laminates for the printed wiring board industry, and new and improved polyimide films. The measurement standards in this example include standards embodied in infrastructure technologies developed through combining efforts of industry and federal laboratories, specifically at the National Institute of Standards and Technology (NIST). The respondent reports that for its research investments it participates in industry associations such as IPC—Association Connecting Electronic Industries—where its researchers can network with NIST personnel, and it uses publicly available high-frequency signal test methods for printed wiring boards and measurement standards to which test equipment may be calibrated with the measurements traceable to NIST.

To begin our calibration of the model, we ask the respondent to consider a hypothetical typical R&D project in the area of industrial research as just described and to estimate the

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[10] Our survey is available on-line in Scott and Scott (2013).

expected value of $x$ (as described in Section II) and the probability of $x$ being at least 25 percent greater than expected. The respondent for the example used for our illustration answered that the expected value of $x$ was 125 and the probability of $x$ being at least 25 percent greater than expected was 0.075. For simplicity we assume a normal distribution for $x$, and for the normal distribution with expected value $x$ we can then solve for the standard deviation for the distribution.[11] The standard deviation is 21.7.[12] Thus, the standard deviation is 17.4% of the mean, and for our simulations as R changes and shifts the distribution, we maintain the standard deviation at 17.4% of the mean.

R&D effort is normalized so that $R_i = 100$ corresponds to the level of effort actually chosen by the respondent; with that effort, from the response above, the expected value of $x$ is 125. Continuing our calibration of the model, we next ask the respondent for the expected value of $x$ if the company's research effort were to vary up or down while the R&D effort of rival companies did not change. In this example, the respondent reported that if its R&D effort were to decrease by 25 percent while the R&D effort of rival companies did not change, the expected value of $x$ would be 90. On the up side, the estimate was that at 125% of its actual R&D with rivals R&D held constant, the expected value of $x$ would be 135, would be 145 at 150% of actual R&D, and would be 150 at 200% of actual R&D. Thus, for this respondent we have the pairs for $E(x)$, the expected value of $x$, and for $R_i$: (90, 75), (125, 100), (135, 125), (145, 150), and (150, 200).

We have assumed that $f(x)$ is normal and that its mean has a simple functional relationship to $R_i$, namely $\int x f(x; R_i) dx = c \log(R_i) + d$, where the parameters $c$ and $d$ are chosen with ordinary least squares to fit the responses to the questions about the pairs for $E(x)$

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[11] Alternatively, because the gamma distribution is also determined by two parameters, we can get similar results assuming that distribution. Although the gamma distribution has the intuitive appeal of its skewed shape (that as it shifts rightward becomes more like a normal distribution) and a domain of the positive numbers, we use the more familiar normal distribution. In fact, for the parameterizations implied by the respondents' answers, typically the gamma distribution has approached an approximately normal distribution for relative quality over the positive numbers and appears symmetrically bell-shaped and with very small probability, often essentially zero, over the research outcomes with very poor relative performance.

[12] We solve for the standard deviation such that the integral of the distribution from 156.25 (which is 1.25 times 125) to infinity is 0.075.

and for $R_i$.[13] For this respondent, $E(x) = 59.6\log(R_i) - 158$, with the standard deviation of the distribution at 17.4 percent of its mean.[14]

We next asked about the relative differences, for different values of $x$, in the present value of the future stream of profits from innovation from the R&D. We asked the respondent to think about the value of R&D results as follows:

> Imagine an index of the value to your company—the present value to your company of the stream of future profits in the post-innovation market available to provide a return on the R&D investment—associated with a given index of R&D quality. Normalize this value index so that the value of equaling the quality of the best R&D outcome among rival companies is 100 (i.e., the value index is 100 when the R&D quality index, considered above, is 100). A value index of 125 would describe a situation where the expected profit stream has a present value 25% higher than the profit stream that would be expected if your company's R&D index was 100.

Thus, the value $V(x)$ associated with equaling the quality of the state-of-the-art technology is normalized at 100; i.e., $V(100) = 100$. We then asked the respondent for an estimate of what the value index would be if the company's R&D quality index were 110, if the quality index were 125, and if the quality index were 150. In the example we are using, the respondent estimated that the value of $x$ would be 105 given $x$ equal 110, 110 given $x$ equal 125, and 120 given $x$ equal 150. Thus, for the example, we have $V(x)$ and $x$ pairs of (100, 100), (105, 110), (110, 125), and (120, 150).

To continue our calibration of the model, we assume the value function has the simple functional form $V(x) = a + b\log(x)$ if $x > 0$, and $V(x) = 0$ if $x \le 0$ (because the company will in such cases of extraordinarily bad outcomes not commercialize the results of R&D).[15] Also, we assume the value function passes through the point (100, 100). Thus, $V(x) - 100 = b(\log(x) - \log(100))$. The parameter $b$ is then chosen to fit the responses for the $V(x) - 100$ and $\log(x/100)$ pairs. Thus, for this example, we use ordinary least squares with the

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[13] Throughout, we use log to denote the natural logarithm, sometimes denoted ln. We have chosen the simple functional form to minimize the number of parameters estimated.

[14] Adjusted $R^2 = 0.844$, $F(1, 3) = 22.56$, and the probability of a larger $F = 0.018$.

[15] Our simulation results are insensitive to a variety of alternative assumptions about the value for the extraordinarily poor research outcomes because the survey responses imply that the probability of such outcomes is very low and often essentially zero.

pairs $(5,\log(1.1)),(10,\log(1.25)),(20,\log(1.5))$. The regression provides the estimate of $b$, and then $a = 100 - b\log(100)$. We have $V(x) = 48.4\log(x) - 123$.[16]

Using the estimated functions for $V(x)$ and $E(x)$, and keeping the standard deviation of the distribution for $x$ at 17.4% of the mean as the distribution is shifted by changes in $R_i$, we can compute $G(R_i) = \int V(x)f(x;R_i)dx$ and the slope of $G(R_i)$ at $R_i = 100$. In this particular case, the slope at $R_i = 100$ is found to be 0.248.

Therefore, profit-maximization implies the cost per unit of R&D investment is 0.248. This gives us the value for $w$ that reconciles the normalizations of $V(100)$ and $R_i$; $w = 0.248$ will remain constant as the functions for $V(x)$ and $E(x)$ shift in the counterfactual scenarios we examine.[17] Moreover, present expected innovation value can now be expressed as a multiple of research expenditure, a figure that typically is available or can be reasonably estimated. In this example, the net present value for the hypothetical project, $G^* - wR_i^*$, is 3.3 times the present value of the R&D costs, $wR_i^*$.[18] Since $G$ is some fraction of the total expected social value, including spillovers, generated by the firm's R&D effort, it is possible to express that social value also in dollars.

## IV. The Importance of Standard-Setting Organizations and Public Support

With a sufficiently large sample of firms, in industries with different market structures and belonging to different SSOs, there is much useful insight to be gleaned from the preceding information alone. However, we want to address the impacts on R&D investment and performance of public infrastructure technology for measurement standards and also SSOs and other industry associations involved with standards. We ask about hypothetical, counterfactual situations in which first the government labs and their support for infrastructure technology are absent from the standard-setting activities. We then ask about the counterfactual situation where

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[16] Adjusted $R^2 = 0.997$, $F(1,2) = 1126$, and the probability of a larger $F = 0.0009$.

[17] See the Appendix for details.

[18] $G^* = 106.499$ and $wR_i^* = (0.248)(100)$. Our results are not very sensitive to the assumption of normal distribution with the standard deviation a constant fraction of the mean. We reach very similar results by ignoring the distribution altogether, supposing that the company maximizes *not* $G(R_i) - wR_i = \int V(x)f(x;R_i)dx - wR_i$, but instead $V(E(x)) - wR_i$.

SSOs and other industry associations supporting standards activities are absent. The firm estimates how $f(x;R)$ and $V(x)$ could be expected to change in these counterfactual cases.

**The First Counterfactual: The Absence of Standards Support from Public Laboratories.** For the first counterfactual, we ask the respondent whether NIST or other public labs have played a significant role in the development of technology standards most relevant to the company's research efforts in the area of research relevant for the hypothetical project being discussed. The respondent for the particular case study being described here reports:

> Volunteers from NIST and other labs . . . participate as either leaders or participants on many of the standards development committees and task groups. As such, they bring discipline to these efforts by ensuring that any round robin testing is done in a quality manner as well as helping to ensure that the standards that are developed are done in a manner that uses science as a basis.

We then ask the respondent:

> . . . to imagine a counterfactual situation ***without*** the involvement of NIST or other public labs in the standard-setting process. Try to imagine this situation, given the best response of your company, rival companies, and relevant industry organizations in the absence of this public support.

In our example, the respondent estimated that in the counterfactual case the R&D effort needed to achieve a given (expected) quality index would be 25 percent higher:

$$E(x) = \int x f(x;R_i)dx = 59.6\log(R_i/1.25) - 158 = 59.6\log(R_i) - [59.6\log(1.25) + 158].$$

This implies a leftward shift in the distribution and a rightward shift in the $G(R_i)$ function. Facing a more difficult R&D problem, the optimal level of R&D effort increases and net present value falls, as depicted in Figure 2.

**FIGURE 2 ABOUT HERE**

The effect on the relation between R&D and quality is not the entire story. For our illustrative example, the respondent reports that the value in the post-innovation market would also be 10 percent lower in the counterfactual case because of what the standards are doing for production and commercialization. Thus, $V(x) = (0.90)[48.4\log(x) - 123]$. This has the effect of reducing optimal R&D effort and reducing NPV. If the distribution-shifting effect and the value-reducing effect on optimal R&D effort offset exactly, then these NPV-reducing effects reinforce each other, and as depicted in Figure 3, NPV is reduced while R&D investment stays the same.

In the present case, the value-reducing effect is offset slightly by the distribution-shifting effect, and the amount of R&D investment in the counterfactual case for the hypothetical project increases by 1.0 percent to 101.0 percent of the effort when the public support for standards activities is present. In the actual case, $G^* - wR_i^*$, is 3.3 times the present value of the R&D costs, $wR_i^*$. For the counterfactual case without the support of national laboratories, the ratio of the net present value, $G^* - wR_i^*$, to the present value of the R&D costs, $wR_i^*$, is 2.6.

**FIGURE 3 ABOUT HERE**

We described above for the benchmark case how to turn $G$ into a dollar amount, and we can do the same thing in the counterfactual case—using the model and the answers to a few questions, we can estimate that the number is a certain percent of actual R&D expenditure, and then we can look at what the firm spends on R&D in a typical year. As in the benchmark case, we would want to apply an appropriate multiplier to the value the firm captures in order to get the social value, including spillovers. The difference between the social value in each case provides an estimate of the social value that is attributable to the government lab's role in standard-setting—looking just at this one firm and any spillovers from this firm's activity.[19]

**The Second Counterfactual: The Absence of Standards Support from SSOs and Industry Associations.** For the second counterfactual, we ask the respondent whether SSOs or industry associations played a significant role in the development of technology standards most relevant to the company's research efforts being discussed. The respondent for the illustrative case study answers yes and reports:

> The standards developed by SSOs create a framework within which we do our R&D in that many of the needed physical properties are identified and the range of acceptable levels is also specified. Without this information, it would be much more difficult to develop products that would be useful to a wide range of companies. This is because the effort of obtaining "Voice of the Customer" from each customer would be very difficult. In addition, the standards help to provide general agreement on how

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[19] When there is a difference, as there is in the present case being used for illustration, in private R&D effort between the actual and counterfactual cases, either because of additional effort in the counterfactual case to replicate the lab's contribution or because of complementarities between public and private research crowding-in additional private investment in the actual case, then that would also enter into the calculation. For example, additional private investment in the actual case would need to be subtracted from the additional value attributable to the public lab.

> the physical properties should be measured, thus avoiding miscommunication between the developer . . . and the customer.

Next we ask the respondent:

> . . . to imagine a counterfactual situation ***without*** the involvement of SSOs and industry associations in the standard-setting process. Try to imagine this situation, given the best response of your company and rival companies in the absence of SSOs and industry associations.

In this counterfactual situation without SSOs and industry associations, the respondent reports that the R&D effort required to achieve a given R&D quality index would increase by 50%. Moreover, the value of R&D outcomes would decrease by 30% in the absence of the SSOs and industry associations.

In this counterfactual, without the SSOs and industry associations to support the standards work, the net present value for our respondent's hypothetical research project falls to about half of its value given the SSOs and industry associations.[20] The net result of the distribution-shifting and value-shifting effects on R&D investment is to decrease the investment to 93% of what it would be with the SSOs and industry associations.

**Sample Averages: Comparisons of Impacts for the Counterfactual Scenarios.** Future research might obtain the cooperation of one or more SSOs or industry associations for a large sample study based on the views of their members' R&D managers and researchers; Chiao et al. (2007) provide a list of such organizations. Here we have case studies of R&D projects described by respondents (some identified during earlier evaluation projects reviewed in Link and Scott (2013)), who responded to our request for their opinions. In addition to the responses used above for the step-by-step illustration of the model, we had an additional six sets of responses to the survey about product and measurement standards.[21]

Our respondents included companies working with standards in a variety of ways. Among the respondents were those who described their work as follows, beginning with the description paraphrased from the respondent who provided the foregoing illustrative example.

- Research and product development related to the supply of new and innovative materials for the manufacture of printed wiring boards including flexible copper clad laminate substrates, coverlay and bondply materials, photoimageing materials, and high performance insulating

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[20] (65.044 –( 0.248)(93))/(106.499 –(0.248)(100)) = 0.51.

[21] The correspondence with the respondents and interviews occurred in October and November of 2012 and in April and May of 2013.

films:  Technology standards that are most relevant to the research efforts are developed by industry associations such as IPC Association Connecting Electronic Industries, SMTA (Surface Mount Technology Association), IEEE and others related to electronics manufacturing.  These standards cover a variety of areas including printed wiring board materials, printed wiring board manufacturing, assembly and quality.  Publicly provided infrastructure technologies used in this area of industrial research include high frequency signal test methods for printed wiring boards, creation of standards to which the test equipment may be calibrated and participation in industry associations such as IPC, Association Connecting Electronic Industries, where the researchers can network with NIST personnel on an individual basis.

- Research and product development for mobile devices with standards being an integral part of both the products and the research to develop them—research about wireless technologies and standards—wide-area network, local area Wi-Fi, and even more local with Bluetooth and Near Field:  The research and product development enables production by mobile device manufacturers.  Important are interconnect standards, standards for wiring within devices, and standards-related R&D to enable transmission and reception of images from cameras to computer/device displays.  Very fast links and huge amounts of data are exchanged.  There is R&D about sensors, for example for ambient light, for microphones, for GPS, for gyroscopes—all involve standardized interfaces.  The R&D is about developing capabilities for moving large amounts of data, exchanging it, and storing it in devices.

- Research and product development for safe electronics and better design of Human Machine Interface (HMI) products that improve performance and reduce costs for machine control and process measurement applications, for example in oil and gas exploration:  A HMI is in general a computer and display integrated in a rugged enclosure, usually with a touchscreen interface for operator interaction but sometimes serving solely as an information terminal.  Typically the HMIs are connected to a higher level system such as a server on a drilling platform or an array of sensors in the case of process measurement.  HMIs in such an environment must survive extreme environmental exposure to hot and cold temperatures, and must be useable in both daytime and nighttime conditions.  They must meet very rigid international certification standards for explosive atmosphere safety because of the risk of volatile gasses being present in the environments.  Important for the research and product development are standards regarding product attributes for explosive environments, product interfaces including Ethernet, fiber optic, and USB, and measurement standards for displays, for product environmental testing and product development processes.

- Research and product development for computer applications in medical imaging, including image display techniques and display device calibration:  Important for the research and product development are CIE standards for measurement of luminance and chromaticity, NIST standards for calibration of luminance and color measuring devices, DICOM standards administered by NEMA for image storage and transmission and perceptual linearization calibration, and VESA display metrology standards.

- Compliance testing and R&D for developing test facilities for the testing of product compliance to new standards:  Products are tested for compliance to energy efficiency, electrical safety, and telecommunications interoperability standards.  R&D develops test procedures with specialized testing infrastructure and test methods to ensure that outcomes of testing will prove a product complies or fails to comply with national and international standards. Important are standards for electrical safety in telecommunications, home entertainment equipment, and power supplies, and for energy efficiency in lighting, IT, power supplies, and home entertainment equipment.

The respondents report that they work with standards written by committees that include industry, laboratory test facilities, government representatives, industry and trade associations, SSOs, and other interested parties. They work with national laboratories such as NIST and with the support of SSOs and trade associations and private labs.

For each scenario, we asked each respondent for an approximation of the proportion of the typical research project's total value that would not be captured by the company but would spill over to other firms (as producer surplus) and customers (as consumer surplus). These approximations of spillovers are used for estimating the social value of the R&D projects.

Table 1 provides the averages of key metrics for the actual scenario for the seven respondents who discussed product and measurement standards. The seven observations in Table 1 represent different types of firms: large and diversified (three observations), large and focused (one observation), medium-sized with some diversification (one observation), and small with R&D that is fairly focused (two observations).

**Table 1 ABOUT HERE**

In five of the seven cases summarized in Table 1, the respondent also provided the description of the counterfactual scenario without the support of public laboratories. Table 2 provides the averages for the changes in the key metrics for the counterfactual case where the companies do not have the public laboratory support for their use of standards. R&D investment falls by 8.3 percent, the private benefit-to-cost ratio falls by 13.8 percent, and the social benefit-to-private-cost ratio falls by 32.5 percent.

**Table 2 ABOUT HERE**

In five of the seven cases summarized in Table 1, the respondent provided the information about the counterfactual scenario without the support of SSOs or industry associations. Table 3 provides the averages for the changes in the key metrics for the counterfactual case where the companies do not have the support of SSOs and industry organizations. In that counterfactual, R&D investment falls by 34.5 percent, the private benefit-to-cost ratio falls by 19.1 percent, and the social benefit-to-private-cost ratio falls by 59.1 percent.

**Table 3 ABOUT HERE**

## V. Overview of the Effects of Standards Enabled by SSOs and Public Laboratories

There are multiple effects on R&D incentives as intellectual property (IP) protection is strengthened or weakened by the use of standards. One effect can be through a change in the proportion of the value of innovative investment that is captured by rivals—that is, not appropriated by the innovator. We elicit respondents' assessment of this proportion in both the public lab and SSO scenarios, in both the actual and counterfactual situations. But while each firm fails to capture some of the value that it creates, for that very reason each will benefit from the value created by its rivals' research projects. Comparing our counterfactual cases with the actual situation, we can observe the net effects of the spillovers received and the spillovers lost.

Note that standards enabled by SSOs and public labs provide value as a public good, and so their effect on the amount of IP protection is different from policy interventions that change the rules governing IP protection. Such rules changes, which in contrast to standards do not add value in the form of a public-good asset as they strengthen or weaken the amount of IP protection, imply a tradeoff between the incentive for innovative effort and the size of the pool of knowledge on which this effort draws (Stiglitz, 2014). Standards, while also affecting the strength of IP protection, may at least partially escape this tradeoff. Standards could conceivably increase incentives for innovative investment while expanding the relevant pool of knowledge and making it more accessible.

In our model, the effect of standards on the appropriability of the value of innovative investments operates through two channels: Standards affect the value of relative performance and the probability distribution over relative performance. These effects can, perhaps somewhat subtly, be likened to changes in IP protection, although they comprise a more complicated set of relations than simply the strength of a patent measured in various ways (such as the length of legal patent protection, the length of time before rivals can invent around the patent, the increase in an innovation's profit margin because of the patent, etc.). Introducing standards on the one hand can make the proprietary products of a company more valuable and so in the abstract strengthen IP protection—in the sense of increasing the private value of IP. The standards can increase the private value of any given amount of IP at any given level of nominal IP protection (conferred by patent regulations and other relevant legal institutions), and can conceivably do so in a way that is not zero sum even among rival firms, because the standards themselves are valuable as public-good assets. On the other hand, because the standards allow more companies to compete with their proprietary products, standards can also weaken IP protection—in the sense of decreasing the private value of IP. Specifically, by intensifying competition, standards could reduce the value that a given firm is able to appropriate from its IP—albeit while increasing the social value of the IP. Thus, standards both strengthen and weaken IP protection, and our method allows us to see on balance the overall effect on innovative investment and performance.

Support for standards, provided by public laboratories and SSOs and industry associations, has a large impact on the private and social value of industrial research. The finding is consistent with what our respondents say in their prose descriptions of the importance of the support they receive from public laboratories and SSOs and industry associations. One respondent wrote: "Without efforts of [the SSOs and industry associations] with NIST support, there would be total anarchy and chaos. SSOs level the playing field for researchers large and small." Another respondent stated that without support for standards provided by SSOs and industry associations:

> Manufacturers will try to separate themselves from others by implementing non-standardized processes and then let the market choose the winner. It is hard to learn if you are not part of a group that has a common goal.

Responding to the question: "Have SSOs or industry associations played a significant role in the development of technology standards most relevant to your company's research efforts?" another respondent wrote:

> Our entire marketplace relies on industry standards . . . . Because of the standards, we all work to the same relatively level playing field. Without those standards, all customers would have unique and often conflicting requirements making standard product development for this market a nightmare. We also rely heavily on business process standards such as ISO-9001:2000 and AS-9100 to both better our own operations and provide a framework for customers to evaluate our suitability as

> qualified suppliers. Without this framework, more arbitrary and less objective methods might be employed to qualify suppliers leading to more uncertainty and chaos in the marketplace.

Our findings are also consistent with our respondents' views that, without standards supported by public laboratories and by SSOs and industry associations, there would be a dramatic decline in the quality of the products and services they create. Commenting about the decline in the expected quality of the state-of-the-art in the counterfactual case without SSOs and industry associations, one respondent observed:

> . . . without performance standards, development efforts would be customer specific and more random yielding much lower ROI, hence much lower total investment. Innovation would be harder to find because the prevailing problems would be harder to identify. Less effort combined with less consensus on the problems to be solved would yield much lower quality and innovation of solutions.

Table 4 summarizes the respondents' statements about the decline in quality that would result without SSO and national laboratory support for standards and their use.

**Table 4 ABOUT HERE**

## VI. Regulatory Standards to Change the Direction and Rate of Technological Change: The Case of Fuel Efficiency

Public policy to promote innovation aimed at reducing pollution may be especially desirable, because the underinvestment in new technology is likely to be greater when the principal value of the new technology is to reduce a negative externality and the technology is therefore likely to be underappreciated in the market (Jaffe, Newell, and Stavins, 2005). If the price drivers pay at the pump does not reflect the full social cost of that gasoline, their willingness to pay for new technology that improves a vehicle's fuel efficiency will not reflect the social value of having that technology. It is an open question whether fuel efficiency standards are an effective policy in this context.

To analyze the impact of the new CAFE standards on automotive R&D investment, we use an interview-guide/survey with essentially the same questions about the probability distribution for relative outcomes from a firm's R&D and the value of those outcomes. Also, we use essentially the same questions about R&D effort and value for the counterfactual scenario of interest. For the analysis of the impact of the new CAFE standards, the counterfactual scenario is the situation without the new regulations.

Crandall et al. (1986, p. 117) found that the original CAFE regulations did not have much impact because ". . .the Arab oil embargo and the subsequent rise in the real price of motor fuel would surely have induced a response from the automobile companies and consumers in the absence of fuel economy regulation. Automobiles would be much more fuel efficient today even if the government had not chosen to regulate fuel efficiency." Crandall et al. introduce methodology to estimate the impact of regulation apart from the improved fuel efficiency as the market responded to higher gasoline prices, and conclude (Crandall et al., 1986, p. 135): "Overall, it appears that the improvement in fuel economy for the industry was very close to what would have been expected without the CAFE standards." White's seminal study (1982) found that while the direct regulation of the emissions from vehicles reduced air pollution, the design of the emissions regulation was not optimal and caused costs that could have been avoided, a conclusion forcefully echoed by Crandall et al. (1986, pp. 115-116).

The analyses of Crandall et al. (1986) and White (1982) were retrospective; they examined the history that unfolded after the original CAFE and emissions regulations. In contrast, we use our model to project the impact of the new CAFE 2025 regulations; thus the analysis here is prospective rather than retrospective. We ask automobile-industry R&D managers about parameters of the R&D investment model and then simulate what is expected to happen. Our findings project outcomes that inform both the understanding of the impacts of the new regulatory standards and any future modifications to those standards. The understanding shows the importance of strategic partnerships to enable fuel-efficiency objectives of public policy while promoting economic growth and development.

The announcement of the new CAFE standards prompted considerable thought and discussion from the automotive industry. *Automotive Engineering International*, the trade journal for the Society of Automotive Engineers, published several articles (Ashley, 2012; Brooke, 2012; Costlow, 2012) about how the industry would respond to the new standards. The articles quoted automobile industry experts' opinions about the response, and we wrote to the quoted experts and requested their help with our research. We also contacted the R&D organizations of the major automobile manufacturers with the same request. Eight of the potential respondents agreed to help develop our case studies of CAFE-related R&D projects by responding to the survey questions and talking with us about the anticipated R&D-investment impact of the new CAFE standards.[22]

As explained in the introduction, the discussion of Mansfield et al. (1977, p. 222) about the limitations of samples of respondents willing to discuss industrial R&D projects is directly relevant, so we could not expect to get a large sample. Moreover, the sample obtained cannot be considered random, although we have no reason to think that our sample is biased in ways that would cause us to find effects for the new CAFE standards that would differ from what we would find with a larger sample. Our eight respondents came from four different parts of the automotive supply chain. Two of the responses are from senior R&D managers explicitly stating that they are responding on behalf of the companies' directors for R&D (to whom we had written) at two of the world's largest automakers. Two of the responses are from R&D managers (one of these also the Chief Technical Officer) for companies supplying major components and materials to the automobile manufacturers. Another two responses are from R&D experts from automotive consulting and engineering research companies.[23] Finally, two respondents were R&D managers for a major collaborative R&D project bringing together companies from

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[22] Potential respondents were contacted and survey responses and interviews and follow-up discussions with the respondents were conducted during the period from February through August of 2013.

[23] For the consulting firms, where appropriate such as with questions about the value of the research to the companies working with the research firm to accomplish an R&D project, the respondents were asked to respond to the questions about the research projects from the standpoint of the companies doing the research with the consulting firm. So, for the questions about private value, the respondents were asked to "[i]magine an index of the value to companies using the research with which [company name] is involved (the present value of the stream of future profits in the post-innovation market, available to provide a return on R&D investment)." Then, subsequently, for the counterfactual, they were asked: "How would the value to companies using the research with which [company name] is involved . . . of a given R&D quality index change?" For the questions about spillovers from R&D activity used to get from private to social value, for the consulting firms the survey stated: "Typically, a company will not capture all of the value of its R&D outcomes. Other companies often benefit by observing the technology and applying what they learn to their own R&D efforts. Consumers using products embodying the new technology will receive benefits greater than the price they pay because competition keeps price below what they would be willing to pay. Because the benefit from R&D in part spills over to consumers and other producers (and in the case of R&D aimed at improving fuel economy and reducing emissions also spills over to others beyond those using the technology, but here we focus on consumers and producers that actually use the technology), the value captured by successful innovators is likely to be less than the total social value created. As a rough estimate, what percentage of the total social value (for users of the technology) of the R&D outcomes of the research with which [company name] is involved can the companies developing the research with [company name] expect to capture? That is, what percentage of the total social value will NOT spill over to others?"

throughout the automotive supply chain and the scientists and engineers and physical laboratory resources of the Oak Ridge National Laboratory (ORNL).[24]

In their descriptive statements about their organization's R&D, the respondents indicated that the research is applicable to internal combustion vehicles, hybrid electric vehicles, plug-in hybrid vehicles, and all-electric vehicles. Five of the eight respondents reported that applications of the R&D in which they are actively involved are primarily anticipated for all four of those categories.[25] One of the eight respondents said that the company's research was primarily applicable to internal combustion and hybrid electric vehicles, and secondarily applicable to plug-in hybrid and all-electric vehicles. One respondent said the company's research was primarily applicable to hybrid electric, plug-in hybrid, and all-electric vehicles and secondarily applicable to internal combustion vehicles. One respondent reported that the company's research was primarily applicable to internal combustion vehicles and secondarily applicable to hybrid electric, plug-in hybrid, and all-electric vehicles.

For the case studies of the six automotive industry companies, we applied the same method explained in Sections II, III, and IV. Table 5 shows the averages of private benefit-to-cost ratios, private net present value-to-cost ratios, and the ratios of social value to private costs. On average, private net present values of CAFE-related R&D investments are positive—the private benefit-to-cost ratios exceed 1.0. Social benefit-to-cost ratios are much higher.

**Table 5 ABOUT HERE**

However, when we examine the changes in the evaluation metrics for the counterfactual scenario of no new CAFE standards as compared to the situation with the new 2025 standards, we find a dramatic difference from what we saw in Section IV when comparing the counterfactual and actual situations for measurement and product standards. SSOs and public laboratories were seen by industry as supportive, and we found that without such support, the performance of industrial R&D deteriorated. However, our discussions with industrial

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[24] Again, for the collaborative project at ORNL, when appropriate such as with questions about the private value of the research, the respondents were asked to respond from the standpoint of the firms collaborating in the project. For example, see the material below about the spillovers question in the discussion of the ORNL project.

[25] These four categories were listed in our survey/interview guide. It also had a category for "other" applications, and one of these five respondents also listed "fuel cell vehicles" in the "other" category.

respondents reveal that from industry's perspective, the new CAFE standards are redirecting R&D efforts and some respondents believe that there would be greater value for industrial R&D efforts in the absence of the new standards. Those respondents believe that market forces would cause the automobile industry to respond to the demands of consumers and that the value of R&D directed at satisfying those demands would far exceed the value of the R&D that is necessitated for the industry to satisfy the new 2025 CAFE mandates.[26]

Simulating the parameterized model for the six case studies finds that for only one of the six companies is the social benefit-to-cost ratio for its CAFE-related R&D expected to be greater given the new CAFE 2025 mandates than without them. The private value of that company's R&D is also greater with the new standards. That one company is one that is ahead of the curve and has recently developed new process technology allowing it to secure sufficient orders to be able to build new production facilities in 2013 for its innovation of components that "light-weight" automobiles and therefore improve their fuel-efficiency. The current R&D of that company is aimed at further improving process technology and reducing further the cost of producing its "light-weighting" innovative products. For two of the respondents, the CAFE 2025 mandates have not changed the fuel-efficiency-related R&D they do—in one case because the company was committed to improving its fuel-efficiency-enhancing technology even without the new standards and in the other case because the majority of the company's sales are outside the U.S. For the remaining three companies, the responses to our questions imply that both the private value of their R&D and its social value would be greater without the new standards. For two companies, given the new standards, the CAFE-related R&D projects have a measured negative net present value, but the companies nonetheless do the R&D to be able to meet the new standards.[27]

Table 6 shows the averages for the proportional changes in the metrics for the counterfactual case without the new CAFE standards. In the counterfactual case, the expected

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[26] Given the historical record, discussed by White (1971, pp. 228-247; 1982, pp. 11-23), of the automobile industry's response to the initial government concerns about emissions and safety, some observers will be skeptical of the industry's views about the difficulties that must be surmounted to meet the new CAFE 2025 standards. However, our R&D investment model, parameterized with what we believe to be the honest assessments of industry experts about abstract parameters of the model, supports the view that the industry's concerns are real and not simply self-serving attempts to avoid the challenge of the new standards.

[27] As discussed subsequently, the net present values for the two companies are negative assuming no funding constraints.

value of innovation is higher by 76.4 percent, R&D investment falls by 8.5% (on average although there is more value, less R&D effort is required, and that dominates), the private benefit-to-cost ratio increases by 83.3 percent, and the social benefit-to-private-cost ratio increases by 39.0 percent. Although the results show an increase in private and social value without the new standards, because the averages are pulled in the opposite direction by the one company that has already had success with its CAFE-related R&D efforts, the averages are not significantly different from zero. The social values are lower bounds because they are based on just the spillovers of value to the industry's consumers and to other firms rather than any additional social value to those outside the market because of the reduction in fuel consumption and any associated reduction in emissions. Thus, in the cases where a respondent's answers imply that the new CAFE standards are associated with a reduction in social value for the consumers and firms in the automotive industry, that is not inconsistent with an increase in social value if there is sufficient social value created for those outside the industry because of reducing energy dependence and reducing emissions.

**Table 6 ABOUT HERE**

There are a variety of possible interpretations for the two cases where given the new CAFE standards, the CAFE-related research for a company has a measured negative present value; we focus on two.[28] One interpretation is that there may be negative net present value for a company's current R&D as it develops a program to meet the new standards, or to improve other aspects of performance while meeting the standards, or to be ready to assimilate fuel-efficient technologies created by others. The company may hope for a breakthrough in its research helped by spillovers from the research of others. Doing the R&D, even though at the moment it does not itself appear to create enough of commercial value, may ultimately help in the assimilation of research results from others (Cohen and Levinthal, 1989). The company may also do the research, figuring that if a good faith effort is made and the prospects stay dim, it may help

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[28] A third possibility of course is that the measured negative net present value results because the respondent did not correctly describe the relations from R&D effort to relative performance and from relative performance to value. After all, that is one reason why there is an error term in the estimation of the averages in Tables 5 and 6.

convince the government to relax the mandate.[29] Also, the regulators may not relax the CAFE 2025 standards, but the research projects, augmented with spillovers that the company can assimilate, may well get the desired results, but just at a cost higher than what can be covered with sale of the improved products since consumers are not expected to be willing to pay enough for them given the relatively low price of gasoline in the U.S.

A second explanation for the measured negative net present values is that funding constraints result in a downward bias in the net present value we measure. If R&D funding is less than the optimal amount because of a binding constraint, the estimated slope of the iso-NPV line is biased upward and its intercept (indicating the actual NPV) is therefore biased downward. Figure 4 illustrates a situation where the measured NPV is negative. The steepest of the iso-NPV lines is the one measured assuming there is no funding constraint, and its intercept with the vertical axis indicates the measured negative NPV. If there is in fact a funding constraint, the true iso-NPV lines are the flatter ones. The unconstrained optimum occurs where the higher of these two flatter iso-NPV lines is just tangent to the $G(R)$ function. The actual NPV at the constrained optimum is the intercept of the lower of the two true iso-NPV lines shown.

**Figure 4 ABOUT HERE**

The two cases with negative net present value for actual CAFE-related research are both cases where underfunding of the research would be understandable and even likely. In one case, almost all of the company's sales are outside of the U.S. Assigning a small portion of the R&D budget to developing fuel-efficient technology may be a way to enable assimilation of such technology developed by others even though the expectations for the value of their own research results are low.[30] In the other case, the company's leadership believes strongly that the new CAFE standards are forcing the new technology with the likely result being that consumers will not be willing to pay enough to cover its costs. The company may be doing CAFE-related R&D to stay in the game with the underfunded research while waiting to see if the U.S. government

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[29] See White (1982, pp. 22-23, pp. 72-77) for historical examples of delays in the dates by which automobile regulatory standards were to be met, for discussion of the reasons strict enforcement of mandated dates for achieving regulatory standards are not credible, and for discussion of companies doing R&D as a part of a good faith effort that could be used to support rescinding a mandated requirement when a company tried to meet the requirement but found the challenge too difficult.

[30] See Cohen and Levinthal (1989).

will rescind or delay the new standards and also to be better able to assimilate ideas from the R&D of others.[31]

For each of the two cases where we observe negative net present value for CAFE-related R&D given the new CAFE standards, we can estimate what the actual net present value would be if the R&D projects have been funded at less than the optimal level as illustrated in Figure 4. To do that, we use the average cost per unit of normalized R&D effort for the other four companies as the cost per unit of R&D effort, and then solve for net present value at the chosen (underfunded) R&D effort. We can also find what the fully-funded optimal level of R&D effort would be using the estimate of the cost per unit of R&D effort and then solving for the level of R&D effort where the marginal value of R&D effort equals its marginal cost.

The second part of Table 5 shows the R&D evaluation metrics given the interpretation that the two cases where net present value appeared to be negative were cases where there was indeed a funding constraint. The two cases of negative net present value are replaced with the positive net present value at the current suboptimal level of funding as illustrated in Figure 4. For one of the cases, the optimal R&D effort would be 81% more than the actual funding-constrained effort if in fact the negative NPV measured was the result of a funding constraint. The optimal NPV would be 116, while the actual NPV would be 83.0, while the measured NPV was -40.7. If the funding constraint story is the correct explanation, removing the constraint would increase NPV by 40%. For the other case of measured negative NPV, the optimal R&D effort would be 73% more than the actual funding-constrained effort—again assuming the measured negative NPV resulted from a funding constraint. The optimal NPV would be 72.4, but the actual NPV would be 48.1, and the measured NPV was -46.6. Assuming there is indeed a funding constraint, if it were removed, NPV would increase by 51%. Assuming those constraints, the average for each metric of course increases somewhat as reported in the second part of Table 5.

To show the impact of the CAFE regulations on R&D, we used Table 6 and showed how the metrics for R&D evaluation changed in the counterfactual case without the CAFE 2025

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[31] White (1982, pp. 73-74) observes ". . . the manufacturer may realize that EPA's and Congress's notions of what are feasible levels of stringency and reasonable dates of achievement are derived at least partly from the research done by the industry. Hence, the manufacturer may well decide to slacken the pace of its research, especially if it feels that other manufacturers are likely to reason and behave in a similar fashion."

standards. The changes shown in Table 6 are a good description with or without the assumption of funding constraints for the two firms that have negative net present value for their CAFE-related R&D given the assumption that there are no funding constraints. Assuming funding constraints, results for the Table 6 metrics are essentially the same since only two firms are affected by the alternative funding-constraint analysis. One of those reports no changes in the counterfactual case, and for the other the changes for effort and value reported remain the same with or without a funding constraint and the metrics have numerators and denominators that move in the same direction when the changes in the counterfactual case without the new CAFE mandates occur.

To see if the funding-constraint interpretation affects the metrics of Table 6, we considered two possibilities for funding in the counterfactual case. For one possibility, we assumed that if the new CAFE mandates were rescinded, the one company (for which the Table 6 metrics would change) would continue at the same constrained level of R&D effort. For the other possibility we assumed that if the new CAFE mandates are removed, instead of staying at the same R&D effort the company would fully fund the R&D. That assumption fits with our sense of what the company would do given our discussions with its president/CEO and with its chief economist. Both think the fuel-efficiency enhancing research would be many times more valuable and take substantially less effort in the absence of the new CAFE standards. So in addition to re-computing the company’s Table 6 metrics under the assumption that the funding constraint would not be lifted in the counterfactual case, we also recompute the metrics assuming it would fully fund the research without the mandates. Under either set of assumptions, the metrics in Table 6 change very little for the one company where there would be changes; thus, the findings in Table 6 would change very little.

In the counterfactual case without the new CAFE standards, if the company chooses to fully fund the fuel efficiency research that would emerge in the counterfactual case, it would choose to increase R&D effort from what it actually is with the new CAFE standards. However, this increase would still be less than that needed to fully fund the research in the actual case with the new standards. The reason fully funding the research in the counterfactual case increases R&D less than the difference between the optimal funding and the constrained funding with the new standards is that in the company’s view without the new regulatory standards and the “technology forcing” they entail, it would take just a third as much effort to achieve the same relative performance.[32] Thus, even though the company's leadership believes the research would have much more value if the company were free to respond to consumers' demands for new technology and hence the consumers would be willing to pay for it, combining the two effects results in a smaller increase in R&D effort at the counterfactual optimum than the increase to the fully-funded level in the actual case with the new regulatory standards.

In sum, since the one company for which the Table 6 metrics would change shows very little change, the averages shown in Table 6 change very little if the funding constraint interpretation is used. Thus, the story that emerges from Table 6 about the impact of the new CAFE standards on automotive R&D activity and performance is also unchanged. Table 7 shows how the Table 6 metrics change for the one company with different metrics if the funding constraint interpretation is used.

**Table 7 ABOUT HERE**

We have circumstances where companies find that the new direction for technology (that the government acting on behalf of society wants) is one for which the customers of the product do not want to pay. Crandall et al. (1986, pp. 5-6) describe the economic problem that underlies the use of regulatory standards to achieve results that the market would not produce. The problem is that "a very tight 'technology forcing' schedule of regulations" would result in "high priced problem cars that consumers reject," and older vehicles that create the negative externalities would be used even longer. It is therefore especially important to consider adding to the R&D mix the use of public/private partnerships to develop the new technology.[33]

Just such a partnership is exemplified by the Oak Ridge National Laboratory (ORNL) collaborative project for developing new processes to provide cost-effective light-weight

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[32] White (1982, p. 21) observes that in the 1970s regulatory targets for emissions "were acknowledged by all to be beyond the existing technological capabilities of the automobile manufacturers; the targets were specifically designed to be 'technology forcing.'" The new CAFE 2025 standards are also technology forcing.

[33] The market failure argument for government support of "precompetitive generic enabling" technology (Scherer, 1999, p. 57) is especially pertinent here where a government regulatory mandate requires R&D investments to produce innovations for which consumers may not be willing to pay enough to allow the firms to recoup a normal return on their investments. The policy requiring the R&D investments itself creates an "appropriability problem" (Scherer, 1999, pp. 53-59). Automobile manufacturers cannot appropriate the social value of the new fuel-efficient technology because automobile consumers are unwilling to pay a sufficient amount for the technology.

materials for automobiles. One of our two respondents from ORNL described ORNL's program in carbon-fiber technology as follows:

> Program goal is to develop technologies that will provide lower cost carbon fiber with properties required by automotive designers. Carbon fiber composites can lower vehicle weight by 50-67% but are far more expensive than traditional automotive materials due primarily to the high cost of the carbon fiber. The current program looks at all technologies affecting the cost of carbon fiber and seeks to reduce the cost of each of those elements.

We asked the ORNL-R&D-manager respondents our questions about the probability distribution of the research outcomes, the effort to achieve various expected outcomes, and the value of those outcomes to the corporate participants. We also asked about expectations for the proportion of the social value that those corporate participants would be expected to capture, stating:

> Typically, the corporate participants in the ORNL collaborative effort will not capture all of the value of its R&D outcomes. Other companies often benefit by observing the technology and applying what they learn to their own R&D efforts. Consumers using products embodying the new technology will receive benefits greater than the price they pay because competition keeps price below what they would be willing to pay. Because the benefit from R&D in part spills over to consumers and other producers (and in the case of R&D aimed at improving fuel economy and reducing emissions also spills over to others beyond those using the technology, but here we focus on consumers and producers that actually use the new technology in their use or production of lighter weight automobiles), the value captured by successful innovators is likely to be less than the total social value created.
>
> As a rough estimate, what percentage of the total social value (for users—consumers and producers—of the technology) of ORNL's R&D outcomes in the carbon-fiber project can the corporate participants in the ORNL collaborative effort expect to capture? That is, what percentage of the total social value will NOT spill over to others?

In contrast to the case studies for the CAFE-related R&D of the companies, for the collaborative research project at ORNL, with the private sector working with the government laboratory and with government funding, the optimal organizational behavior for the ORNL collaborative effort maximizes the net present value for the *social* value of the research. Thus, in the model of the ORNL R&D project, we divide the corporate participants' private value function by the proportion of social value captured by the corporate participants in the ORNL collaborative project. Observe that the resulting social value is a conservative lower-bound estimate because it reflects the spillovers of R&D value to other firms and to consumers, but it does not reflect the additional social value to those outside the automobile market from reduction in energy dependence and emissions.[34] With the probability distribution for the research outcomes and its relation to R&D effort and with the social value function, we can compute the present value of the ORNL public/private partnership's R&D as a function of R&D effort. Figure 5 shows that function.

**Figure 5 ABOUT HERE**

The current R&D investment in the ORNL project is normalized at 100; and we can develop an argument for additional public support for the project as follows: The public/private partnership is constrained on the funds available, and our model shows that additional public support is needed to maximize the social net present value of the cooperative investment.

To see why, we first observe that a reasonable estimate of the cost per unit of R&D effort for the ORNL project would be the average unit R&D effort cost for our respondents, namely 0.867—the average of the $w$ estimated for each of the six companies providing the case studies summarized in Tables 5 and 6. Then to maximize the social net present value, R&D effort will increase until the slope of the social present value curve shown in Figure 5 is 0.867. At the current level of effort, the slope is greater than 0.867, so more R&D resources should be devoted to the project, but the allocation of public funds to such a project is subject to the political process that is *not* using the maximization of social net present value as the criterion for determining the funding. The optimal amount of funding is such that $G'_{social}(R)$ is 0.867. As seen in Figure 5, rather than being the current level of R&D effort, normalized at 100, the socially optimal amount of R&D investment is for R&D effort $R$ of 161 which is an R&D investment of $wR$ equaling about 140.[35]

The model supports the belief that public funding should be used to increase the R&D investment in the ORNL project by at least 61% (since the social value estimate is a conservative lower bound). The lower-bound social benefit-to-cost ratio with optimal funding is about 5.2. The lower-bound social benefit-to-cost ratio with current funding is about 4.8.

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[34] The value to those outside the automobile market is not something about which we would expect our respondents to know.

[35] Multiplying 161 by 0.867 we obtain 139.6.

Many industrial organization economists will believe that we have been too optimistic about the benefits of strategic partnerships in the automobile industry. Our analysis of the ORNL collaboration assumes optimal organizational behavior, but it may be that the conflicts between the companies and the broader public interest will prove too difficult to overcome. One conflict is the lack of appropriate pollution taxes on fuel for motor vehicles (Scherer, 1996, pp. 326-327). Another conflict results because automobiles are status goods, and many consumers get utility from having a bigger, more powerful car than their neighbors (Scherer, 1996, p. 326). The combination of the first and second conflicts causes automakers to worry that consumers will not be willing to pay enough for fuel-efficient automobiles to cover the costs of developing new fuel-efficient technologies (Scherer, 1996, p. 328). Moreover, automakers strategically worked around the original CAFE standards by heavily marketing so-called light trucks, including SUVs, that had easier CAFE targets and higher margins. Also, regarding the initial efforts to regulate automobile emissions, agreement among industry members was focused on avoiding pollution control devices, not implementing them (Scherer, 1996, p. 329; White, 1971, p. 231). Thus, history offers many reasons to believe that we have an overly optimistic view of the benefits from the ORNL strategic public/private partnership.

However, the ORNL project is notably a public/private partnership rather than a private cooperative effort as was the mid-1950s Automobile Manufacturers Association's cooperative R&D program to study pollution control devices for automobiles as discussed by White (1971, p. 231) and Scherer (1996, p. 329). Physically located at a national laboratory and with R&D management from the laboratory and with substantial public funding, the collaborative effort in the public/private partnership to develop precompetitive generic enabling technology is much more likely to be effective at introducing innovation than was the private trade association effort in the insular U.S. auto industry of the mid-1950s. Yet, given the major conflicts between the private companies and the broader public interest in improving fuel efficiency and reducing pollution, we must be circumspect and temper our enthusiasm about the strategic partnerships. It is one thing to say we need responsible leadership from industry and government and the institutions of civil society; it is quite another thing to actually manage good solutions given all of the conflicting incentives.

## VII. Discussion.

**The New Evaluation Approach: Normalizations Enable Interview-based Parameterization of the R&D Investment Model.** We have presented a new approach for evaluating the impact of standards on R&D investment and its private and social value. Although we apply the theory in Scott (2009) and Scott and Scott (2014), this paper breaks new theoretical ground. We have converted the abstract theory into a discussable interview guide by introducing two key normalizations: the value of research results that equal the anticipated state of the art is normalized at 100, and the firm's current R&D effort is normalized at 100. These normalizations make it possible to discuss with industrial respondents the theoretical, relative R&D performance relations. The two key normalizations are then reconciled in the new applied theory, so that after the discussion with a respondent, all the pieces can be assembled into a coherent description of how R&D investment is affected by standards of various types. In principle, the approach can be used to analyze the impact on investments and performance of many other counterfactual scenarios. In addition, we provide a new method for exploring the implications of R&D funding constraints in both private and public settings.

Importantly, our approach accounts for competition because first we find the basic relationships in the model as the firm changes what it is doing given what rivals are doing and assuming the firm and its rivals are at their equilibrium, and second we ask the firm how those relationships would change in the counterfactual equilibrium given that rivals make the adjustments to the new equilibrium. The questions are worded so as to accommodate either competitive or Nash non-cooperative equilibrium.

Ideally, future research will develop large samples of respondents across many different industries, different types of research, and different types of firms, apply our methodology to the large samples, report the findings, and provide econometric analysis of the large sample findings. Creating large samples will be difficult for two reasons. First, as Mansfield et al. (1977, p. 222) explain, companies are often not willing to provide information about their R&D projects because the information is considered sensitive proprietary information. We have addressed that concern in part by discussing with our respondents not absolute amounts but instead relative amounts. R&D performance is measured relative to the anticipated state of the art; R&D effort is normalized relative to current effort; and the value of R&D results is normalized relative to the value of the anticipated state of the art. There is a second reason that it will be difficult to develop large samples. From our work with the respondents for the 14 case studies in this paper, we have learned that respondents find it challenging to answer questions about the functional relationships between R&D effort and the relative quality of the R&D results and between relative quality and commercial value.[36]

We emphasize that once the right individual (or a set of colleagues) in the corporate R&D hierarchy has been found, and given that the individual is willing to work with us either in an interview or with iterative questions and answers as the respondent completes the survey, informed estimates of the relationships can be made. In the interview or iterative question and answer process, we emphasize to the respondents that we would like them to think broadly about their estimates of the relations explored—for one example, to get a sense of whether R&D performance is expected to increase less than proportionately, proportionately, or more than proportionately with R&D effort. We explain that their opinions about such relationships will be helpful as informed approximations based on their actual experience with the types of R&D projects being described.

**Standards and Strategic Alliances: Public/Private Partnerships Enable Standards.** The ORNL collaborative research project is an obvious case of a public/private partnership, but in fact all three types of standards examined in this paper entail public/private partnerships. National laboratories typically work closely with industry as new measurement technologies and standards are developed, and the process in which industry uses measurement standards traceable to a national laboratory requires public/private partnership for the success of the ongoing communications between industry and the national laboratory. SSOs' standard-setting activities entail strategic partnerships among firms and also there is often use of expertise from national laboratories as standards are developed and used. The ORNL project is a collaborative research project operated at a national laboratory and bringing together firms from the various parts of the automobile industry's supply chain that will be supported by the research.

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[36] At first look, it may appear that we are asking too much of respondents, who must respond with estimates of expected values and probabilities that correspond to a theoretical model. Undoubtedly the questions are more challenging than the sorts of questions often posed in surveys. However, with the normalizations, we have developed the abstract theory to make it accessible for discussion with appropriate respondents with first-hand knowledge of the R&D investments. Such respondents can indeed formulate answers with some effort. Often formulating the answers comes only with multiple follow-up discussions as the respondents think, based on their experience, about whether the quality of R&D outcomes increases proportionately or more or less than proportionately with R&D effort, or whether the commercial value of the outcomes increases proportionately or more or less than proportionately with the quality of outcomes.

The strategic alliances embodied in the public/private partnerships toward standards support technology-based economic growth with policies that range from the passive supportive role of measurement standards (such as for the measurement of the wavelength of light in a fiber optic system[37]), through the more active shaping of the direction of technological change with product standards (such as a compatibility standard as for USB ports that work with a wide array of peripheral devices) to the most active redirection of technological change with regulatory standards (such as the CAFE 2025 standards). The more passive measurement standards are the most even-handed in that they do not typically determine the direction of technological change but enable that change, whatever direction the market takes. Such passive measurement standards find essentially unanimous support from the participants in the public/private partnerships that develop and enable them. Of course, at times there are disagreements about the desirable pace for the advancement of such standards, with times when industry says more rapid development of national and international standards would be commercially desirable and then other times when industry reports that the national laboratories have developed measurement standards beyond the level needed for the current commercial applications.[38] But, there is general agreement that the measurement standards are needed for effective commerce.[39]

In contrast, regulatory standards that actively shape the direction of technological change are often met with antipathy toward what is seen as government intrusion in the workings of the market.[40] Indeed, our respondents on the whole believe that an increase in the gasoline tax would be a better way to induce fuel-saving innovations than the new CAFE standards because when facing higher gasoline taxes consumers would be more willing to pay for the new innovations. Current U.S. policy takes the approach not of using taxes to raise gasoline prices to induce a consumer driven demand for fuel-saving innovations, but rather takes the "technology-forcing" approach of the new fuel-efficiency standards, which—although developed in

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[37] Link and Scott (2005).

[38] Examples are provided in Link and Scott (2012, pp. 45-80).

[39] For examples of the general support for measurement standards, as well as the examples where the pace of the development of the standards is behind or ahead of the needs of industry, see the case studies in Link and Scott (1998, 2011, 2013).

[40] Some observers believe that performance will be better when strategies exhibiting corporate social responsibility (CSR) originate from the companies themselves as they respond to the demands of their customers. For an exposition and discussion in the context of the automotive industry of the view that CSR strategies developed by companies in response to their customers' needs will be less costly and have greater value than "coerced" strategies that are mandated by government regulations, see Funyak (2013).

cooperation with industry and consumer advocacy groups—seem to be receiving a mixed reception at best. Given that resistance, to keep the relatively low fuel prices while inducing innovations for fuel efficiency, strategic partnerships bringing together industry and government laboratory resources, such as the cooperative research project at ORNL, are especially important.

To inform the debate about the conceptual merits of market-driven versus government-mandated directions for technological change, our approach provides a pragmatic evaluation. We evaluate the performance effects of the passive, supportive measurement and product standards and also the more active, technology-path-directing regulatory standards to address negative externalities. Pragmatic evaluation can get beyond what could be seen as self-serving statements of participants in the regulatory process.

For both the passive, supportive standards and the more directive, regulatory standards, the statements of those affected by the standards can be self-serving. With the passive, supportive standards, companies get something—infrastructure technology support at the taxpayers' expense. With the regulatory standards, the companies perceive that technology is being pushed in the direction of innovations for which consumers may not be willing to pay. Industry and many consumers then see a coerced direction for technological change that infringes on freedom to choose the path and pace of technological change. In such circumstances, strategic partnerships bringing consumers, industry, and government together are critical. To provide input to support the success of such partnerships, we use our model, parameterized using the views of industrial R&D managers, to look pragmatically at what is likely to happen as industry responds to the new CAFE standards.

We have discussed with industry experts the abstract, big-picture parameters of the R&D investment process modeled to allow evaluation of equilibrium outcomes in counterfactual circumstances of interest. Our model can encompass and evaluate both the views of those believing market driven technological change would be better and those believing government-directed technological change is needed. Our approach can explain and address pragmatically the economics of the innovation value created with scarce resources and compare the outcomes for the various scenarios. Strongly different perceptions of what is happening are promulgated in the political economy discussion, yet the same investment model can evaluate economic performance implications to inform and corroborate or modify either view.

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# APPENDIX

The two lemmas and two theorems that follow establish the validity of the normalizations of the mean-index function and value function and the use of $w$ to reconcile the two normalizations. The assumed functional forms capture the theoretical relationships as simply as possible to enable estimation with few observations. We assume that these simple functional forms can offer reasonable descriptions of the relationships between (1) expected quality and research expenditure and (2) value and quality when expenditures and value are expressed in dollars. We then show that the normalizations are consonant and describe the same relationships as the actual non-normalized relationships (Theorem 1) and remain valid as the functions change to describe the counterfactual scenario (Theorem 2).

Lemma 1: If $\hat{V}(x) = \hat{a}\log(x) + \hat{b}$ is the present dollar value of the relative quality outcome indexed by $x$, then there exists a function (our normalized function) $V(x) = a\log(x) + b$, with $a = 100\hat{a}/(\hat{a}\log(100) + \hat{b})$ and $b = 100\hat{b}/(\hat{a}\log(100) + \hat{b})$, such that (i) $V(100) = 100$ and (ii) $V(x')/V(x) = \hat{V}(x')/\hat{V}(x)$ for any two index values $x$ and $x'$.

Proof of (i): Let $V(x) = a\log(x) + b$, with $a = (100\hat{a}/(\hat{a}\log(100) + \hat{b}))$ and $b = (100\hat{b}/(\hat{a}\log(100) + \hat{b}))$. Substituting for $a$ and $b$, factoring out 100, and rationalizing the fractions, then $V(100) = 100$.

Proof of (ii): Again, let $V(x) = a\log(x) + b$, with $a = (100\hat{a}/(\hat{a}\log(100) + \hat{b}))$ and $b = (100\hat{b}/(\hat{a}\log(100) + \hat{b}))$. In $(V(x')/V(x)) = (a\log(x') + b)/(a\log(x) + b)$, substitute for $a$ and $b$, factor out 100 from the numerator and the denominator and cancel, and rationalize the fractions in the numerator and the denominator to have $V(x')/V(x) = \hat{V}(x')/\hat{V}(x)$.

Corollary: If there exists a function (our normalized function) $V(x) = a\log(x) + b$, with $b = 100 - a\log(100)$ so that $V(x) = 100$ when $x = 100$, and such that $V(x')/V(x) = \hat{V}(x')/\hat{V}(x)$ when $\hat{V}(x')$ and $\hat{V}(x)$ are the present dollar values of the relative quality outcomes indexed by any $x'$ and $x$, then the actual present discounted value as a function of quality is $\hat{V}(x) = \hat{a}\log(x) + \hat{b}$ where $\hat{a} = (\hat{V}(100)/100)a$ and $\hat{b} = (\hat{V}(100)/100)b$. That is because from the first lemma, $a = 100\hat{a}/\hat{V}(100)$ and $b = 100\hat{b}/\hat{V}(100)$.

Lemma 2: If $E(x) = \hat{\mu}(R) = \hat{c}\log(R) + \hat{d}$ is the expected value of the relative quality outcome index $x$ when the present dollar value of research outlays is $R$, then there exists a function (our normalized function) $\mu(R) = c\log(R) + d$, with $c = \hat{c}$ and $d = \mu(\widetilde{R}) - \hat{c}\log(100)$, such that (i) $\mu(100) = \hat{\mu}(\widetilde{R})$ and (ii) $\mu(100(R'/\widetilde{R})) = \hat{\mu}(R')$. In words, (i) the expected value of normalized relative quality at the normalized current level of R&D effort equals the expected value of the non-normalized relative quality at the actual (optimal) level of R&D effort. And, (ii) the expected value of normalized relative quality when a given R&D effort is stated as a percentage of the current (optimal) R&D effort equals the expected value of the non-normalized relative quality at that given R&D effort.

Proof: Let the normalized function be $\mu(R) = c\log(R) + d$, with $c = \hat{c}$ and $d = \hat{\mu}(\tilde{R}) - \hat{c}\log(100)$.
Then (i) $\mu(100) = \hat{c}\log(100) + \hat{\mu}(\tilde{R}) - \hat{c}\log(100) = \hat{\mu}(\tilde{R})$, and
(ii) $\mu(100(R'/\tilde{R})) = \hat{c}\log(100(R'/\tilde{R})) + \hat{\mu}(\tilde{R}) - \hat{c}\log(100)$ which equals
$\hat{c}\log(100) + \hat{c}\log(R') - \hat{c}\log(\tilde{R}) + \hat{c}\log(\tilde{R}) + \hat{d} - \hat{c}\log(100) = \hat{c}\log(R') + \hat{d} = \hat{\mu}(R')$

Theorem 1: The normalized and non-normalized relations describe the same equilibrium. Let $\hat{V}(x) = \hat{a}\log(x) + \hat{b}$ be the present dollar value of the relative quality outcome indexed by $x$, and let $E(x) = \hat{\mu}(R) = \hat{c}\log(R) + \hat{d}$ be the expected value of $x$ when the present dollar value of research outlays is R. Suppose also that the probability density function for $x$ is $f(x;R) = f(x;\hat{\mu}(R))$—that is, suppose that the density function depends on $R$ through a single parameter $\mu$.

Let $V(x)$ be defined as in Lemma 1, and let $\mu(R)$ be defined as in Lemma 2 with $\tilde{R}$ the optimal research outlay, so that $\tilde{R}$ satisfies the first-order condition

$$(d\hat{u}/dR)\int\hat{V}(x)(df/d\mu)dx = (\hat{c}/R)\int\hat{V}(x)(df/d\mu)dx = 1$$

Then R = 100 satisfies the analogous first-order condition in normalized units for $V(x)$ and $R$, namely

$(d\mu/dR)\int V(x)(df/d\mu)dx = (c/R)\int V(x)(df/d\mu)dx = w = \tilde{R}/(\hat{a}\log(100) + \hat{b})$, where $w$ the normalized unit cost of research equals the ratio of the optimal R&D investment to the value of the expected state of the art quality. That ratio equals $w$ because from Lemma 1, normalized value $V(x) = (100/(\hat{a}\log(100) + \hat{b})\hat{V}(x)$, and from Lemma 2, normalized expected quality $\mu(R) = c\log(R) + d = \hat{c}\log(R) + (\hat{\mu}(R) - \hat{c}\log(100))$ and so at the current (optimal) effort $\mu(R) = \hat{\mu}(R)$, that is, expected quality is the same for the normalization as it is for the actual function linking effort to quality. Thus, at the optimum,

$\int V(x)f(x;\mu(R))dx = (100/(\hat{a}\log(100) + \hat{b}))\int\hat{V}(x)f(x;\hat{\mu}(R))dx$, and

$(d\mu/dR)\int V(x)(df/d\mu)dx = (100/(\hat{a}\log(100) + \hat{b}))(\hat{c}/R)\int\hat{V}(x)(df/d\mu)dx = w$, and since $R = 100$ and $\hat{c}\int\hat{V}(x)(df/d\mu)dx = \tilde{R}$ from the first order condition in non-normalized units, we then have $w = \tilde{R}/(\hat{a}\log(100) + \hat{b})$.

Proof: The two first order conditions describe the same equilibrium. Starting from the first-order condition with normalized units, satisfied when $R = 100$, we work backwards to obtain the first-order condition in dollars, satisfied when $R = \tilde{R}$. Using Lemma 1 and Lemma 2,

$$(c/100)\int V(x)(df/d\mu)dx = \tilde{R}/(\hat{a}\log(100)+\hat{b})$$

$$\Leftrightarrow (\hat{c}/100)(100/(\hat{a}\log(100)+\hat{b}))\int \hat{V}(x)(df/d\mu)dx = \tilde{R}/(\hat{a}\log(100)+\hat{b})$$

$$\Leftrightarrow \hat{c}\int \hat{V}(x)(df/d\mu)dx = \tilde{R} \Leftrightarrow (\hat{c}/\tilde{R})\int \hat{V}(x)(df/d\mu)dx = 1$$

Theorem 2: The normalizations remain valid in counterfactual scenarios. Let $\hat{V}(x)$ and $\hat{\mu}(R)$ from Theorem 1 be disturbed such that the value and expectation of $x$ are now described by $\hat{\dot{V}}(x) = m\hat{V}(x) = m\hat{a}\log(x) + m\hat{b}$ and $E(x) = \hat{\mu}(R) = \hat{\mu}(R/r) = \hat{c}\log(R/r) + \hat{d}$. In words, technology changes so that the value of any given $x$ increases by $100(m-1)$ percent, and the research outlay required to achieve any given $x$ in expectation increases by $100(r-1)$ percent.

Then, in order to accurately reflect this disturbance when working in the normalized units as defined in Theorem 1, we have only to redefine $V(x)$ and $\mu(R)$ as follows: $\dot{V}(x) = mV(x) = ma\log(x) + mb$ and $\dot{\mu}(R) = \mu(R/r) = c\log(R/r) + d$.

In particular, the normalized unit cost of research remains $w = \tilde{R}/(\hat{a}\log(100)+\hat{b})$.

Proof: In dollars, the first-order condition will be satisfied for $R$ such that

$$(\hat{c}/R)\int \hat{\dot{V}}(x)(df/d\mu)dx = (m\hat{c}/R)\int \hat{V}(x)(df/d\mu)dx = 1.$$

Let us call the optimal research outlay $R^{\$} = m\hat{c}\int \hat{V}(x)(df/d\mu)dx$. In normalized units, the first-order condition will be satisfied for $R$ such that $(c/R)\int \dot{V}(x)(df/d\mu)dx = w = \tilde{R}/(\hat{a}\log(100)+\hat{b})$

$\Leftrightarrow (\hat{c}/R)(100/(\hat{a}\log(100)+\hat{b}))\int \hat{\dot{V}}(x)(df/d\mu)dx = \tilde{R}/(\hat{a}\log(100)+\hat{b})$

$\Leftrightarrow m\hat{c}(100/R)\int \hat{V}(x)(df/d\mu)dx = \tilde{R}$.

Let us call the optimal normalized outlay $R^* = m\hat{c}(100/\tilde{R})\int \hat{V}(x)(df/d\mu)dx$, and notice that $R^* = (100/\tilde{R})R^{\$}$, or $R^*/100 = R^{\$}/\tilde{R}$, showing that the percentage change in the optimal research outlay is the same in either dollars or normalized units.

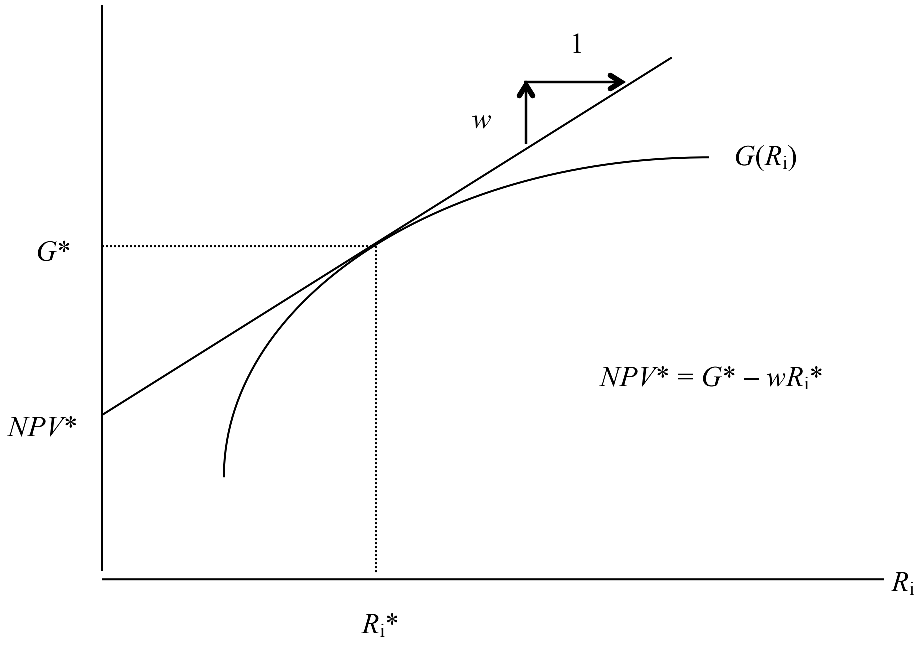

Figure 1. The optimal level of R&D effort $R_i^*$ is at the point of tangency of the iso-NPV line and the expected value function.

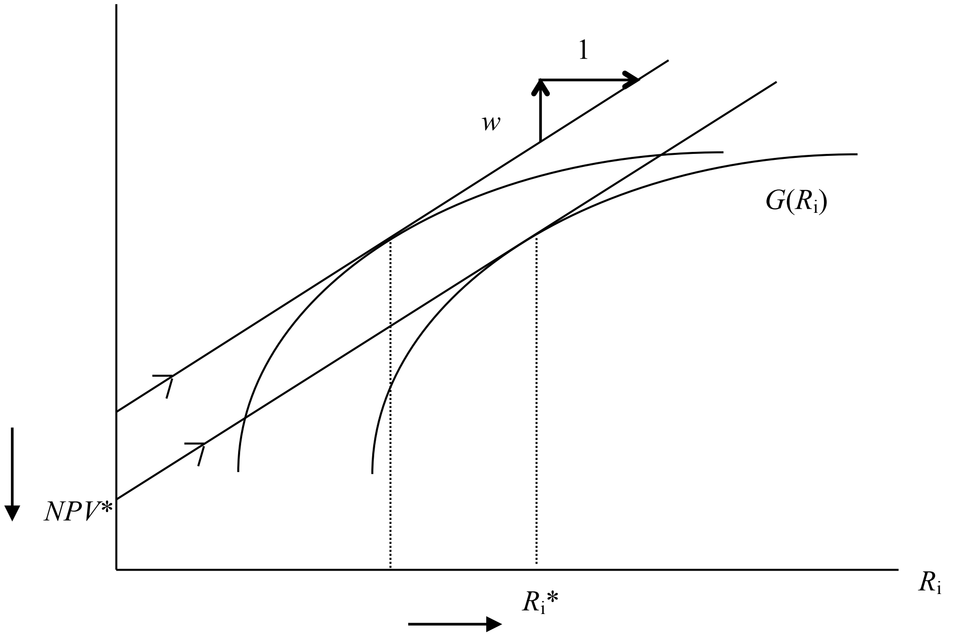

Figure 2. The effect of an unfavorable distribution shift on optimal R&D effort and net-present value.

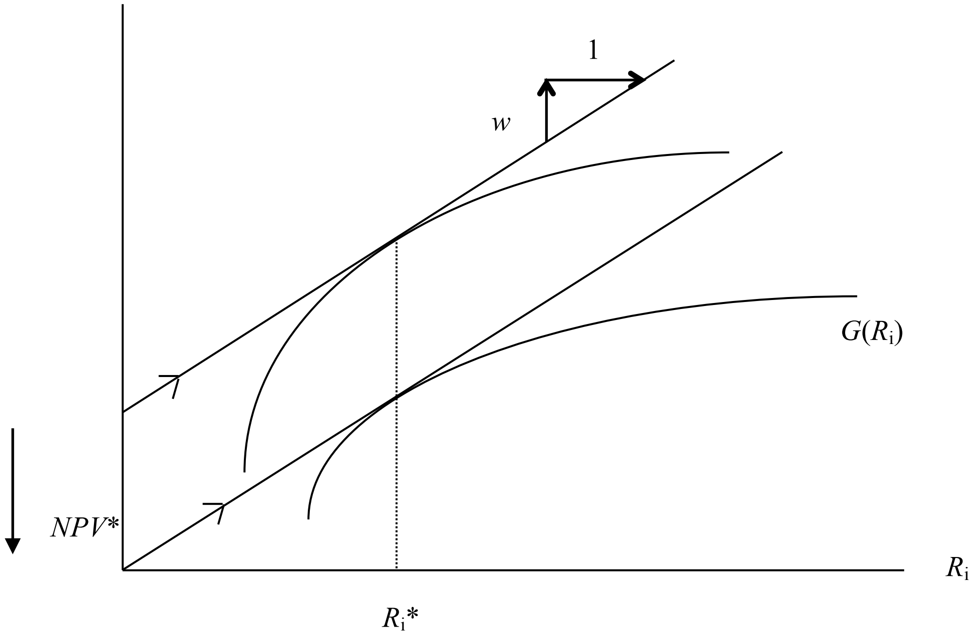

Figure 3. The combined distribution-shifting and value-shifting effects of taking away the government laboratory's role in standard-setting.

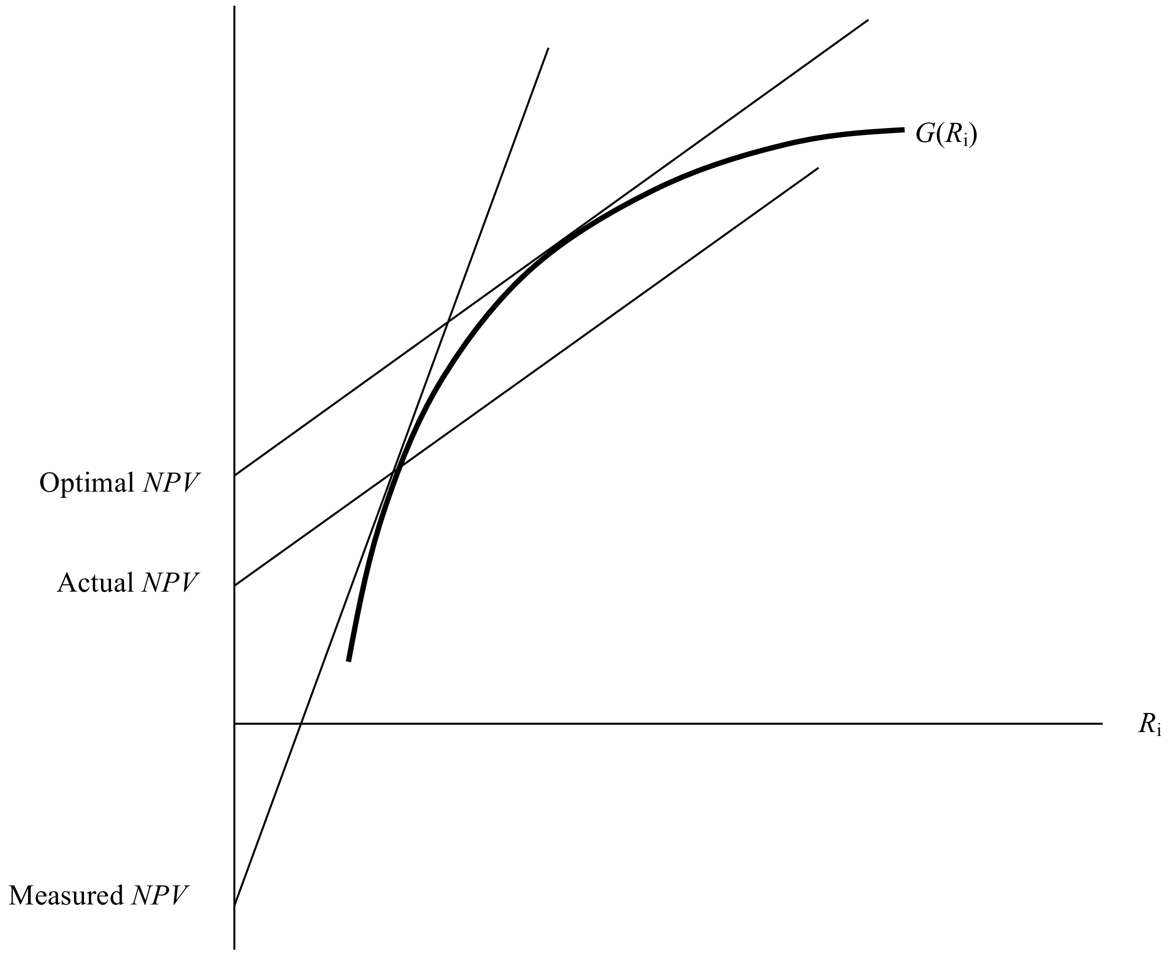

Figure 4. Measured, actual, and optimal *NPV* with a funding constraint.

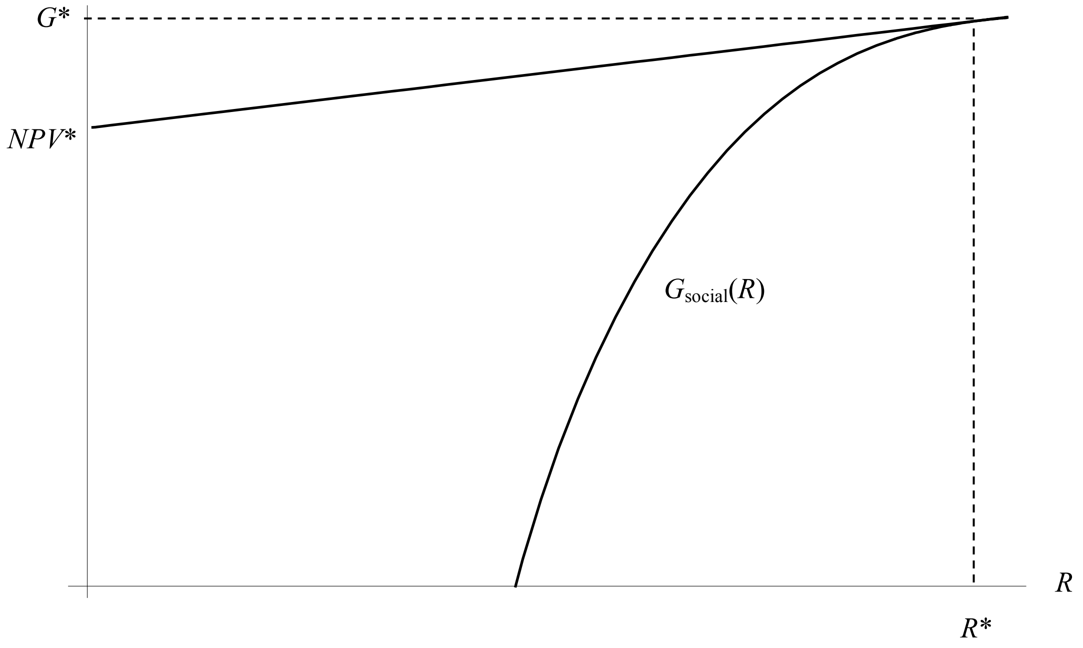

Figure 5. The social value of research effort for the ORNL public/private partnership: $G^* = 730$, $R^* = 161$, $NPV^* = 590$.

**Table 1. Means for Key Metrics for the Research Projects in the Actual Situation, n = 7.***

| Variable | Mean | Standard Error |
|---|---|---|
| Private Value/Cost,<br>$G^*/(wR^*)$ | 7.19 | 3.51 |
| Private Net Present Value/Cost,<br>$(G^* - wR^*)/(wR^*)$ | 6.31 | 3.47 |
| (Total Social Value)/(Private Cost) | 28.3 | 14.0 |

*One of the 7 surveys did not have complete usable answers for questions about R&D effort and the expected quality of R&D outcomes and about expected value of future profits and the quality of the R&D outcomes. In those cases, the average answer from the other surveys was used. We report the standard error for each mean—i.e., the estimated standard deviation of the mean—the sample standard deviation divided by the square root of the sample size. Results in Tables 1, 2, and 3 vary somewhat from those reported in the earliest version of the SSRN working paper (Scott and Scott, 2013) because we have developed the survey responses further, refined the method for computing the slope of $G(R)$, and rather than using the average of the spillover rates reported by the respondents, we have preserved each individual respondent's reported spillover rate to reflect the variance in the firms' ability to protect their intellectual property.

**Table 2. Proportional Changes in Metrics for the Counterfactual without Public Lab Support, n = 5.**

| Variable | Mean | Standard Error |
|---|---|---|
| $\Delta G^*/(G^*_{initial})$ | – 0.201 | 0.0898 |
| $\Delta(wR^*)/(wR^*_{initial})$ | – 0.0834 | 0.0702 |
| $\Delta(G^*/(wR^*))/(G^*/(wR^*))_{initial}$ | – 0.138 | 0.0504 |
| $\Delta(Vsocial/wR^*)/(Vsocial/wR^*)_{initial}$ | – 0.325 | 0.161 |

**Table 3. Proportional Changes in Metrics for the Counterfactual without SSO and Industry Association Support, n = 5.***

| Variable | Mean | Standard Error |
|---|---|---|
| $\Delta G^*/(G^*_{\text{initial}})$ | – 0.470 | 0.145 |
| $\Delta(wR^*)/(wR^*_{\text{initial}})$ | – 0.345 | 0.171 |
| $\Delta(G^*/(wR^*))/(G^*/(wR^*))_{\text{initial}}$ | – 0.191 | 0.0698 |
| $\Delta(\text{Vsocial}/wR^*)/(\text{Vsocial}/wR^*)_{\text{initial}}$ | – 0.591 | 0.144 |

* For one respondent, the absence of the SSO and industry association support was expected to cause such a dramatic deterioration in the firm's R&D performance that it would no longer be profitable and R&D would be abandoned. In that case, each of the first two metrics is – 1.0, and the final two metrics are not defined, so for those metrics, the averages are for just four respondents.

**Table 4. The Loss in Quality in the Absence of Support for Standards.**

As a rough estimate, in the counterfactual case ***without public support*** for technology standards, the expected quality of the state-of-the-art would be ________ percent of the expected state-of-the-art quality ***with*** the public support.

| n | mean | standard error |
|---|---|---|
| 5 | 77.0 | 7.7 |

As a rough estimate, in the counterfactual case ***without*** SSOs and industry associations, the expected quality of the state-of-the-art would be _______ percent of the expected state-of-the-art quality ***with*** SSOs and industry associations.

| n | mean | standard error |
|---|---|---|
| 5 | 60.0 | 6.3 |

**Table 5. Means for Key Metrics for the Automotive Research Projects in the Actual Situation, n = 6.***

Without funding constraints

| Variable | Mean | Standard Error |
|---|---|---|
| Private Value/Cost, G*/(wR*) | 2.35 | 0.911 |
| Private Net Present Value/Cost, (G* – wR*)/(wR*) | 1.35 | 0.911 |
| (Total Social Value)/(Private Cost) | 21.0 | 15.3 |

With funding constraints

| Variable | Mean | Standard Error |
|---|---|---|
| Private Value/Cost, G*/(wR*) | 2.88 | 0.778 |
| Private Net Present Value/Cost, (G* – wR*)/(wR*) | 1.88 | 0.778 |
| (Total Social Value)/(Private Cost) | 25.9 | 15.3 |

*For one of the six cases three questions were not answered, and the average of the answers for those items from the two other firms that did similar research was used. Social values are conservative lower bounds as explained in the text.

**Table 6. Proportional Changes in Metrics for the Counterfactual without 2025 CAFE Standards, n = 6.***

| Variable | Mean | Standard Error |
|---|---|---|
| $\Delta G^*/(G^*_{\text{initial}})$ | 0.764 | 0.773 |
| $\Delta(wR^*)/(wR^*_{\text{initial}})$ | – 0.085 | 0.0867 |
| $\Delta(G^*/(wR^*))/(G^*/(wR^*))_{\text{initial}}$ | 0.833 | 0.730 |
| $\Delta(\text{Vsocial}/wR^*)/(\text{Vsocial}/wR^*)_{\text{initial}}$ | 0.3905 | 0.368 |

* For one of the six cases, three questions were not answered, and the average of the answers for those items from the two other firms that did similar research was used. Changes use estimates without funding constraint. Assuming funding constraints, results are essentially the same as explained in the text. Social value with the new CAFE standards is a conservative lower bound as explained in the text.

## Table 7. Alternative Proportional Change Metrics for the Company with Different Metrics in the Funding Constraint Interpretation.*

| Variable | no constraint | constraint before and after | constraint before |
|---|---|---|---|
| $\Delta G^*/(G^*_{initial})$ | 4.58 | 4.56 | 4.71 |
| $\Delta(wR^*)/(wR^*_{initial})$ | 0.02 | 0.0 | 0.16 |
| $\Delta(G^*/(wR^*))/(G^*/(wR^*))_{initial}$ | 4.47 | 4.56 | 3.92 |
| $\Delta(Vsocial/wR^*)/(Vsocial/wR^*)_{initial}$ | 2.17 | 2.13 | 1.85 |

*This table shows the Table 6 metrics for the one company for which the metrics would change if the funding constraint interpretation is used. The "no constraint" case is the interpretation underlying Table 6 where firms are assumed to fully fund their CAFE-related R&D projects. The numbers reported in the "no constraint" column are the same as those that were used for the company in the averages for Table 6. The numbers for the "constraint before and after" assume that the firm has a funding constraint and will continue to fund the project at the same level in the counterfactual case. The "constraint before" column shows the numbers when there is a funding constraint in the actual case with the new CAFE standards but that R&D is fully funded in the counterfactual case without the new standards.