RIETI Discussion Paper Series 12-E-001

Technology and Capital Adjustment Costs:
Micro evidence of automobile electronics in the auto-parts suppliers

UCHIDA Ichihiro
Aichi University

TAKEDA Yosuke
Sophia University

SHIRAI Daichi
The Canon Institute for Global Studies

RIETI
Research Institute of Economy, Trade & Industry, IAA
The Research Institute of Economy, Trade and Industry
http://www.rieti.go.jp/en/

RIETI Discussion Paper Series 12-E-001
January 2012

Technology and Capital Adjustment Costs: Micro evidence of automobile electronics in the auto-parts suppliers*

UCHIDA Ichihiro — Aichi University
TAKEDA Yosuke — Sophia University
SHIRAI Daichi — The Canon Institute for Global Studies

Abstract

In order to make quantitative evaluations on the nature of capital adjustment costs, in the face of technological changes, we estimate capital adjustment cost functions, either convex, non-convex, or irreversible (Cooper and Haltiwanger, 2006). A simulated method of moments is applied to the Bellman equations at an establishment level of the Japanese auto parts suppliers (Census of Manufactures), where experiencing a technological change of automobile electronics, an application of general purpose technology (David, 1990; Jovanovic and Rousseau, 2005). Identifying when and where auto-electronics technologies have been embodied in the auto parts suppliers, we use patent acquisition data and plants' products items: electronically-controlled fuel injection; electric power steering; anti-lock brakes; airbags; navigation; wire harnesses; and lithium-ion batteries. For the overall auto parts suppliers, there are no adjustment costs in any form, neither convex, non-convex, nor irreversible. As for the sectoral plants with the automobile electronics embodied in the tangible capitals, we clearly detect a significant existence of the convex adjustment costs. Anomalously, auto-electronics also makes investment decisions reversible. Moreover, the fixed costs of plant restructuring, worker retraining, or organizational restructuring emerge, especially in a form of costs proportional to plant size rather than the opportunity cost of investment. The nature of adjustment costs implies economic policy measures to compensate for the output losses from the capital adjustment costs in the face of general purpose technologies.

Keywords: Capital adjustment cost; General purpose technology; Automobile electronics; Simulated method of moments.
JEL classification: O33

* We are grateful to Tsutomu Miyagawa, Naoki Shinada, Shin-ichi Fukuda, Hidehiko Ishihara and workshop participants for helpful comments. We use micro data in the *Census of Manufacturers* and price data in the *Japan Industrial Productivity Database 2010 (JIP Database 2010)*. We appreciate the availability of both data sources. This paper is financially supported by Grant-in-Aid for Scientific Research.

Introduction

The so-called Moore's Law says the number of transistors per integrated circuit would double every 18 months. Similarly, the number of MCU (micro-controller units) installed per vehicle has ever doubled every decade: for middle-class cars on average, 8 in 1980; 17 in 1990; 32 in 2000 and so on (YANO Research, 2009). The *automobile electronics* dramatically changed the concept of cars. As the most pronounced instance, some Japanese automobile constructors developed 'hybrid cars' with built-in devices for fuel injection electronically controlled. Toyota Motor Company launched *Prius* in 1997, followed by Honda *Insight* in 1999 and Nissan *Tino Hybrid* in 2000[1]. During the research and development processes among the constructors and the suppliers of newly-required parts, a change in a trend of market prices of both automobile and auto-parts was marked, as Figure 1 shows. Fluctuation in both prices paralleled with the relative price steady around unity up to 1995. During the 90s second half, however, the motor vehicles encountered price spikes and thereafter the prices remains on a gradual upward trend. By contrast, the auto-parts and accessories unalterably come down in price prior to the 90s and on. In timing, the structural change in the relative prices of the auto-parts coincides with the prominent development of the automobile electronics.

In the face of the automobile electronics developments, how did the auto-parts suppliers adjust to the products innovations of the automobile? In particular, what types of capital adjustment cost did the automobile electronics raise in the auto-parts suppliers? On the specific questions, this paper sheds light from the standpoint of "general purpose technologies" (GPT; David, 1990;

Jovanovic and Rousseau, 2005) exemplified by electricity and computer. As is well recognized by a variety of the products we see the benefits from[2], the automobile electronics makes full use of GPT. It is likely that the GPT requires the auto-parts suppliers to learn by doing capital-embodied technological progress, as literature "investment-specific technology shocks" on adjustment costs suggests (for instance, Hornstein and Krusell, 1996). Thus, a question is raised, whether the automobile electronics is investment-specific technology shock. We

[1] Going back to the beginning, the automobile constructors responded to the first-time emission controls by the Muskie Act (the U.S. Clean Air Act) in 1970. The aim of the Muskie Act was to reduce HC, CO, and NOx emissions by 90% each. The overly strict standard required the Japanese constructors to make it compatible with each other, fuel efficiency and engine performance.

[2] We can list here the products names: engine control; electro AT (automatic transmission)/ CVT (continuously variable transmission); electronically-controlled suspension; ABS (antilock brake system); train control system; electronically-controlled 4WS (4-wheel steering); EPS (electronically-controlled power steering); airbag; corner- and back-SONAR (sound navigation and ranging); driver positional memory; ACC (fully-automatic climate control system); cruise control; RKE (remote keyless entry); navigation; digital meters; multiplex transmission; on-board ETC (electronic toll collection); in-car camera; NVD (night vision device); or tire-pressure monitoring system.

explore quantitatively the effects of the automobile electronics on capital adjustment costs, considering the nature of each type of adjustment costs with convex, non-convex or irreversible functions (Cooper and Haltiwanger, 2006).

Following Cooper and Haltiwanger (2006), we estimate via simulated method of moments the Bellman equations for plants' dynamic optimization with respect to tangible capital, where there are decisions of inaction, buy or sell capitals to choose discretely. Our main results suggest, though the estimates show a lack of stability in the coefficients related to the adjustment costs, that the effects of automobile electronics are mixed, if any. For the overall sample of the auto-parts suppliers, there are no adjustment costs in any form, neither convex, non-convex nor irreversible. As for the sectoral plants where the automobile electronics seems embodied in the tangible capitals, we clearly detect a significant existence of the convex adjustment costs. Regarding another type of the adjustment costs, on one hand, the sell price of the used capitals is anomalously higher than the buy price, which means the auto-electronics makes investment decision reversible. On the other hand, the fixed costs of plant restructuring, worker retraining or organizational restructuring emerge, especially in a form of costs proportional to a plant size rather than an opportunity cost of investment. The nature of adjustment costs associated with the auto-electronics implies economic policy measures which should be taken in order to compensate for the output losses from the capital adjustment costs in the face of general purpose technologies.

The structure of the paper is organized as follows: in Section 1, we present a summary of related literature to the paper, specially focusing on the business cycle theories where technology shocks play a major role accompanied with capital adjustment cost. Next in Section 2, we describe our plant-level data of the Japanese auto-parts suppliers (*Census of Manufactures*), which tangible capitals are measured including the retirements for each plant. Among the items listed in the plant-level data, we can make use of each plant's products, a few of which embody developments in the automobile electronics, an application of general purpose technology. According to another data source of the patent grant, we can identify when and where the embodied technological changes have been engineered owing to the automobile electronics. Section 3 follows, where to present a structural estimation of plants' dynamic profit maximization including either convex/ non-convex or irreversible adjustment cost functions (Cooper and Haltiwanger, 2006). As well as the overall sample of the Japanese auto-parts suppliers, we also apply the structural estimation to partial sample plants identified as embodiments of the automobile electronics. We compare the nature of the capital adjustment costs between the overall sample and the sectoral cases. Finally, we give some conclusions.

1 Related Literature

In this section, we briefly describe some related literature to this paper. Our focus here is on literature of the business cycle theories in which technology changes play a major role. A few of the business cycle literature emphasizes effects of capital adjustment cost on reduced volatilities of macroeconomic variables. Although our paper does not address general equilibrium aspects of capital adjustment costs, our motivation lies in the same line with the following papers mentioned below. Rather, taking a micro evidence of effects of automobile electronics in the auto-parts suppliers, this paper quantitatively makes clear what type of capital adjustment costs matters in the face of such technological changes as the automobile electronics, a fundamental issue that the related literature has never explored.

1.1 Capital Adjustment Cost Function

Penrose (1959) considers shortage of managerial resources as limits to firms' growth, due to "span of control" representing the number of subordinates a supervisor has in a hierarchical organization. Uzawa (1969) adopts Penrose's idea and incorporates into the neoclassical growth model an adjustment cost function $\varphi(I, K) = \phi(\frac{I}{K})K$, where $\phi(\frac{I}{K}) \geq 0$, $\phi^{'}(\frac{I}{K}) > 0$, and $\phi^{"}(\frac{I}{K}) > 0$. The convex adjustment cost function, first-order homogeneous in respect to I and K pins down an optimal investment level I^* in the long run.

On assumptions of the Uzawa's adjustment cost function as well as perfect competitions in products markets, Hayashi (1982) shows in theory an equivalence between the average Tobin's Q and marginal q. Hayashi (1982) also proposes a quadratic form of the convex adjustment cost function $\varphi(I, K) = \xi(\frac{I}{K} - \upsilon)^2 K$. Unlike the Uzawa/ Hayashi adjustment cost function depending on investment rate $\frac{I}{K}$, Christiano, Eichenbaum and Evans (2005) make an alternative function depending on growth rate of investment $\frac{I}{I_{-1}}$, $\varphi(I, I_{-1}) = \xi(\frac{I}{I_{-1}} - 1)^2 I_{-1}$, which can generate volatile fluctuations in the US capital investments to be calibrated with their New Keynesian dynamic stochastic general equilibrium model[3].

1.2 General Purpose Technology

David (1990) in the regard of economic history addresses 'productivity paradox' of such general purpose technology (GPT) as electric dynamo at the turn of the 19th century or the modern computer. The GPTs "occupy key positions in a web of strongly complementary technical relationships that give rise to "network externality effects" of various kinds, and so make issues of compatibility standardization important for business strategy and public policy.(p.356,

[3] Eberly, Rebelo and Vincent (2006) estimate alternative adjustment cost function of either Hayashi (1982) or Christiano, Eichenbaum and Evans (2005; CEE) using the US company data of the *Compustat*, which results in more likelihood of the Hayashi type over the CEE one.

David, 1990)" The GPT also possesses some characteristics: the emergence of an extended trajectory of incremental technical improvement; the gradual and protracted process of diffusion into widespread use; the confluence with other streams of technological innovation (Bresnahan and Trajtenberg, 1996)[4].

The GPT's properties of the improvement, the pervasiveness and the innovation spawning would require firms to learn by doing the GPT itself and its incremental improvement. Like the seminal paper Arrow (1962) on learning by doing, Jovanovic and Rousseau (2002) incorporate into a final/ capital goods two-sector model a learning process $p = \left(\frac{K}{B}\right)^{-\beta}$ meaning that as Moore's Law states, competitive supply of capital K under constant returns to scale leads the price of capital p always equals the average cost of production depending on a constant B. An increase in the parameter β indicating higher learning speed would raise long-run growth but in the transition, decrease speed of the convergence, since a reduction of new capital price causes free riding and thus delayed diffusion lags[5].

1.3 Investment-Specific Technology Shocks

On the cause of the *Great Moderation* in the US economy, Justiniano and Primiceri (2008) quantify relative contributions to reducing the macroeconomic fluctuations. Among structural disturbances in a DSGE model, the key shock determining real GDP growth and the volatility of inflation is 'investment-specific technology shock'. The investment-specific technology shock are a disturbance μ_t in capital accumulation $K_t = (1-\delta)K_{t-1} + \mu_t \left[1 - \varphi(\frac{I_t}{I_{t-1}})\right] I_t$ with the adjustment cost function of Christiano, Eichenbaum and Evans (2005). The investment-specific technology shock can be interpreted as a shock to the relative price of investment in terms of consumption good or a shock to the production technology of capital goods (Greenwood, Hercowitz and Krusell, 1997).

Hornstein and Krusell (1996) also show that the investment-specific technological change may be a cause of the productivity paradox, in a vintage capital model where new technologies with less learning or less experience are introduced at fast rate. Since learning or experience does matter with productivity, the investment-specific technology shock can then reduce measured productivity growth.

[4] In an introductory chapter (Lipsey, Bekar and Carlaw, 1998) to *General Purpose Technologies and Economic Growth*, edited by Elhanan Helpman, a GPT is defined as "a technology that initially has much scope for improvement and eventually comes to be widely used, to have many uses, and to have many Hicksian and technological complementarities"(in page 43). However, none of formal definitions based on theoretical models has been established yet.

[5] For a comprehensive survey on general purpose technology, see Jovanovic and Rousseau (2005).

2 Plant-Level Data of the Japanese Auto-Parts Suppliers

Let us describe data we use for estimation. The plant-level data is from the *Census of Manufactures* compiled by the Ministry of Economy, Trade and Industry, Japan. We treat two sub-groups classified as automotive body and concomitant (classification number 3012) and automotive component and accessory (number 3013)[6].

2.1 Capital Retirement

We consider total tangible capitals including these categories: establishment and structure; machinery and equipment; and ship, vehicle, transport equipment, etc. We exclude land as the capitals we use, since it does not seem that for a unit of each plant, land expansion and contraction can be an adjustment means except for in plant opening or closing[7]. Data on capital retirements is available for our tangible capitals. Here we define the capital stocks at the beginning of period, following the perpetual inventory method:

$$\begin{aligned}
\text{capital stock at the beginning of period:} &\quad K_{t+1} = I_t + (1-\delta)K_t \\
\text{net investment during the period:} &\quad I_t = EXP_t - RET_t \\
\text{gross expenditures:} &\quad EXP_t \\
\text{gross retirements:} &\quad RET_t.
\end{aligned}$$

With regard to how to handle the book value, we follow an equation that retired capitals RET_t is equal to current changes in tangible fixed assets, minus remaining book values of retired tangible fixed assets for multiplied by market-book value ratios[8].

The physical depreciation rate δ is 0.073034 for 1986 to 1992 and 0.09593197 for 1993 to 2007, considering a change in the depreciation rates probably due to higher obsolescence speed or higher shares of software in capital stocks[9]. The deflators for capital category excluding land are ratios of nominal investment

[6] The classification number has been changed in 1985, 2002 and 2008.

[7] In consideration of simultaneity in decision-makings between the tangible capitals and land, we will use the latter as an instrumental variable in estimating profit function where the former capitals are one of the determinants. Nominal land capital is deflated with *the Urban Land Price Index* of the six large city areas (Japan Real Estate Institute).

[8] In terms of how to handle the book values, we try to construct retired capitals RET_t in two another ways else than one described in the text (Tonogi, Nakamura and Asako, 2010). In a method, retired capitals are equal to current changes in tangible fixed assets, minus remaining book values of retired tangible fixed assets for period. The other deals only with current changes in tangible fixed assets. In these two cases, there are some anomalous results in estimations, so that we do not adopt those capital retirements.

[9] We have an alternative of the physical depreciation rates 0 for land, 0.05640 for establishment and structure, 0.09489 for machinery and equipment, 0.147 for ship, vehicle, transport equipment, etc..

Table 1: Summary Statistics (1): Investment Rates in the Overall Sample

Period: 1986 to 2007	Tangible Capital
Average Investment Rate	0.1699
Inaction Rate	0.069
Fraction of Observations with Negative Investment	0.0536
Spike Rate: Positive, Higher than 0.2	0.2937
Spike Rate: Negative, Lower than -0.2	0.00395
Serial Correlation $Corr(i_{it}, i_{it-1})$	0.0305
Correlation w/ Profitability $Corr(i_{it}, a_{it})$	0.1376

matrix to real one in JIP2010: number 33 (non-residential construction) for establishment and structure; 7 (general industrial machinery, including materials handling equipment), 10 (chemical machinery), 11 (metalworking machines), 13 (special industrial machinery), 21 (electricity transmission and distribution apparatus), 22 (electric lighting fixtures and apparatus) for machinery and equipment; and other else (32 capital goods) for ship, vehicle, transport equipment, etc..

We omit some outlier samples with either negative levels of capital K_{it} or anomalous values of investment rate $i_{it} \equiv \frac{I_{it}}{K_{it}}$ at top and bottom 1% of the distribution. Summary statistics is extracted with regard to investment rate in 1. Of the overall sample, inactive plants with $I_{it} = 0$ occupy about 7%. There is a positively skewed distribution with the positive (higher than 0.2) spikes even more frequent than the negative (lower than -0.2) one, the lumpiness and the asymmetry which would lead fixed adjustment costs and irreversibility, in the later estimation. Our data (*the Census of Manufactures)* provides us with a serial correlation 0.0305 of the investment rates, lower than 0.058 in Cooper and Haltiwanger (2006) data(*the Longitudinal Research Database*). The more lumpy capital adjustments also seem to lead dominance of non-convex adjustment cost function.

2.2 Identification of Auto-Electronics Technologies

In order to identify effects of electronics on the capital adjustment costs, we measure some dummy variables representing which products the plants manufacture gain the benefit of electronics technologies, and when the electronics technologies were embodied in the suppliers' capital stocks. The automobile electronics can be thought of as an application of the information technology(IT), a GPT.

On the automobile electronics system, we rely on a detailed description of Tokuda and Saeki(2007a; 2007b; 2007c) explaining in detail modularity and network of the technology[10]. We can decompose the automobile electronics into 4 parts: sensor; ECU (electronic control unit); actuator; and wire harness.

[10] The description covers quite usefully the history and the market shares of the suppliers.

As Figure 2 conceptually shows, the electronics can be compared to anatomy, where human five senses cognize the environment (corresponding to sensor), brain transfers signals from five senses to muscle (ECU), limbs' muscle responds to the signals from brain (actuator), and nerve and vessel connect between the senses and the muscle (wire harness). The 4 parts consist of each market shared by the auto-parts companies as well as the major electric equipment companies. As is seen in the computer industries, compatibility standardization might lead to network externality between each product.

Among the whole systems used for automobile, according to Tokuda and Saeki (2007c), we classify the following products as the electronics: electronically-controlled fuel injection device (PET); electric power steering (EPS); anti-lock brake system (ABS); airbag; navigation system; wire harness; and Lithium-ion battery. We also identify periods when the GPT is innovative associated with the technology listed above, with the number of patents hit by each keyword in the Patent Licensing Information Database.

2.2.1 Products Dummies

Regarding where the auto-electronics technologies are embodied, we draw on a document of Tokuda and Saeki (2007c), which describe main systems for the automobile electronics: electronically-controlled fuel injection device (PET); electric power steering (EPS); anti-lock brake system (ABS); airbag; and navigation system. In addition to the main 5 systems associated with the automobile electronics, we reckon two more products: wire harness and Lithium-ion battery.

Although our criteria for products dummy variables are far from perfect, each system can be interpreted as corresponding to the following commodity indexes in *the Census of Manufactures*: parts, attachments and accessories of internal combustion engines for motor vehicles (#311314) for PET; parts of driving, transmission and operating units (#311315) for EPS[11]; parts of suspension and brake systems (#311316) for ABS; parts of chassis and bodies (#311317) for airbag; radio applied equipment (#301315) for navigation system; parts, attachments and accessories of auxiliary equipment for internal combustion engines (#292221) for wire harness; and Lithium ion batteries (#295113) for Lithium-ion battery.

2.2.2 Time-Dummies for Patent Acquisitions

As for the latter identification for time periods when the electronics was embodied, a criterion we adopt is based on the number of patents for each products associated with the electronics technologies. We additionally use a database in *Industrial Property Digital Library*, which offers the public access to *IP Gazettes* of the Japan Patent Office (JPO) free of charge through the Internet[12].

[11] It includes the automatic transmission (AT) technologies.
[12] It is publicly available from http://www.ipdl.inpit.go.jp/homepg_e.ipdl

Among the databases on intellectual properties submitted to the JPO, the *Patent Gazettes* and the *Unexamined Patent Application Gazettes* are stored databases available to search for the number of patent grants and patent applications, respectively, in Japanese with either keywords, issue dates, or so forth. The Patent Gazettes cover searchable issue dates starting in 1986 up to the present, while the Unexamined Patent Application Gazettes do from 1993 to the present.

We choose time periods during when many cases of patent grants expose themselves in the JPO data. In a case of electronically-controlled fuel injection device (PET), a time dummy variable takes a value 1 from 1986 to 1997 or 0 otherwise. For the PET-time dummy variable, number of observations is 6733. Another time dummy variable for electric power steering (EPS) is 1 for 1999 to 2007 (number of observations 4912). As for anti-lock brake system (ABS), a time dummy variable takes 1 from 2001 to 2007 (number of observations 2031). An airbag time-dummy is 1 for 1998 to 2007 (number of observations 5086); one for wire harness for 1999 to 2007 (number of observations 108); Lithium-ion battery for 2000 to 2007 (unfortunately, number of observations is 0)[13]; and finally, navigation system for 1997 to 2007 (number of observations 17).

Note that our choice of the time-dummy variables is based on casual observations of the numbers of the patent grants identified with the products keywords above[14]. In order to show comparability of our time dummy variables with estimates a_{it} on productivity changes incurred by a plant i classified into ones with electronics innovations at a period t, we estimate correlation ratios η between the time dummy variable and the productivity changes (t-statistics in parenthesis): -0.0797 (-8.67) for the PET-time dummy variable; 0.0366 (3.65) for the EPS-time dummy variable; 0.0567 (4.26) for the ABS-time dummy variable; -0.0011 (-0.11) for the airbag-time dummy variable; 0.0746 (0.99) for the wire-harness-time dummy variable; 0.3004 (1.47) for the navigation-time dummy variable. Among the time-dummies we use, the statistical significance suggests that the EPS-time dummy and the ABS-time dummy variables are better indicators of the automobile electronics technologies.

3 Estimation

We draw on specifications of the functions by Cooper and Haltiwanger (2006). Suppose a production function of the constant-return-to-scale Cobb-Douglas type $y = AK^{\alpha}L^{1-\alpha}$ and an inverse demand function for plant's products with constant price-elasticity $p = y^{-\eta}$. It is a profit function $\Pi = R(y) - wL$ to

[13] We confirm that in our sample there is included a plant of a well-known company as a pioneering producer of Lithium-ion battery, but the plant turns out not to list its products names in a survey for *the Census of Manufactures*.

[14] Some of previous researches that use count data in patent applications, grants and citations are surveyed in Griliches (1990); more recent examples include Griffith, Harrison and van Reenen (2006), or Bloom, van Reenen and Schankerman (2007).

be maximized with respect to a variable factor of production L, labor inputs, where w is a wage rate and a revenue function is $R(y) = py = \left(AK^{\alpha}L^{1-\alpha}\right)^{1-\eta}$. The static profit-maximization leads to a labor demand function

$$L = (1-\eta)^{-\frac{1}{(1-\alpha)(1-\eta)-1}} A^{-\frac{1-\eta}{(1-\alpha)(1-\eta)-1}} w^{\frac{1}{(1-\alpha)(1-\eta)-1}} K^{-\frac{\alpha(1-\eta)}{(1-\alpha)(1-\eta)-1}}$$

and the indirect profit function

$$\Pi(A,w,K) = (1-\eta)^{-\frac{(1-\alpha)(1-\eta)}{(1-\alpha)(1-\eta)-1}} \eta A^{-\frac{1-\eta}{(1-\alpha)(1-\eta)-1}} w^{\frac{(1-\alpha)(1-\eta)}{(1-\alpha)(1-\eta)-1}} K^{-\frac{\alpha(1-\eta)}{(1-\alpha)(1-\eta)-1}}.$$

Summarizing the coefficients in the profit function, we denote

$$\Pi(A_{it}, K_{it}) = A_{it}K_{it}^{\theta} \tag{1}$$

where $A_{it} \equiv (1-\eta)^{-\frac{(1-\alpha)(1-\eta)}{(1-\alpha)(1-\eta)-1}} \eta A^{-\frac{1-\eta}{(1-\alpha)(1-\eta)-1}} w^{\frac{(1-\alpha)(1-\eta)}{(1-\alpha)(1-\eta)-1}}$ and $\theta \equiv -\frac{\alpha(1-\eta)}{(1-\alpha)(1-\eta)-1}$. Intuitively speaking, the more perfect the price competition in a products market is(i.e. the smaller a positive value of η near zero), the higher a value of θ on physical capital K in the profit function.

3.1 Functional Forms of Adjustment Cost

3.1.1 Convex or Non-Convex

Now we incorporate adjustment costs into a dynamic optimization problem. The conventional functional form of the capital adjustment cost assumes convexity. Under conditions of constant-return-to-scale function of adjustment cost with respect to investment and capital stock, Hayashi (1982) shows an equivalence of the average and the marginal Tobin's q in a perfect capital market. The form is

$$C(I,A,K) = \frac{\gamma}{2}(\frac{I}{K})^2 K \tag{2}$$

where a parameter γ indicates the convexity of capital adjustment. The higher the value of γ is, the smoother the capital adjustment is. In an extreme case of $\gamma = 0$ without any adjustment cost, the optimal investment rate will be very responsive to shocks affecting the first-order condition of profit-maximizing agents.

On the other hand, the capital adjustment cost function is also built on non-convexity, capturing existence of fixed costs. The fixed costs are considered as stemming from plant restructuring, worker retraining or organizational restructuring. These costs reflect indivisibilities in capital; increasing returns to the installation of new capital; increasing returns to retraining and restructuring of production activities. A functional form of such non-convex adjustment costs can be specified in the Bellman equation for profit maximization as,

$$\begin{aligned} V(A,K) &= \max\left\{V^i(A,K), V^a(A,K)\right\} \qquad (3)\\ V^i(A,K) &= \Pi(A,K) + \beta E_{A'|A}V(A', K(1-\delta)) \\ V^a(A,K) &= \max_I \Pi(A,K)\lambda - FK - pI + \beta E_{A'|A}V(A',K') \end{aligned}$$

where either active investment $V^a(A,K)$ or inactivity $V^i(A,K)$ is chosen discretely.

In the active case, there are two types of capital adjustment cost. One is an opportunity cost $\lambda < 1$ of investment, which means falls in plant productivity by a factor of $1-\lambda$ of profits. The other type of adjustment cost F depends on the level of capital K in a fixed way proportional to a size of the plant.

3.1.2 Irreversibility

There is another possibility of transaction costs that reflect differentials between buying and selling price of capital. The transaction costs are probably caused by capital specificity or asymmetric information between buyers and sellers. We assume

$$p(I) = \{ \begin{array}{ll} p_b & \text{if } I > 0 \\ p_s & \text{if } I < 0 \end{array} \quad (4)$$

where $p_b \geqq p_s$. The gap between the buying and selling prices will create an inaction region for the plants.

Then the value function of the plants is given by

$$\begin{aligned} V(A,K) &= \max\{V^b(A,K), V^s(A,K), V^i(A,K)\} \quad (5) \\ V^b(A,K) &= \max_I \Pi(A,K) - p_b I + \beta E_{A'|A} V(A^{'}, K(1-\delta)+I) \\ V^s(A,K) &= \max_R \Pi(A,K) + p_s R + \beta E_{A'|A} V(A^{'}, K(1-\delta)-R) \\ V^i(A,K) &= \Pi(A,K) + \beta E_{A'|A} V(A^{'}, K(1-\delta)) \end{aligned}$$

where purchase of new capital I, retirement of old capital R, and inaction of neither investment nor retirement are distinguished with respect to irreversible decision-making.

3.2 Auxiliary Estimation of Productivity Processes

We will take two-step estimations for the Bellman equation of plants' profit optimization problem. In Step 1 as an auxiliary estimation, we estimate a plant's profit function which depends on productivity shocks consisting of an aggregate common shock and plant-specific one. We apply a dynamic panel-data estimation of system GMM (Blundell and Bond, 1998). Following a Tauchen (1986) procedure for discretizing $AR(1)$ process based on the estimates of the productivity processes, in Step 2 we apply a simulated method of moments (SMM) to the Bellman equation of the plants' profit maximization, focusing on the parameters in the capital adjustment cost functions.

In the estimated equation, we make use of a decomposition of a logged productivity $a_{it} = \log A_{it}$ into an aggregate common shock b_t and a plant-specific shock ε_{it}:

$$a_{it} = b_t + \varepsilon_{it} \quad (6)$$

Table 2: System GMM Estimates of Profit Function(1): the Overall Sample

Variables	Coef.	Corrected Std. Err.	Z
π_{it-1}	0.689	0.039	17.78
k_{it}	0.60	0.13	4.73
k_{t-1}	-0.43	0.15	-2.91
log-real GDP_t	-32.96	11.94	-2.76
log-real GDP_{t-1}	33.13	11.96	2.77
log-inter. inputs price_t	-43.28	17.29	-2.50
log-inter. inputs price_{t-1}	-85.25	31.297	-2.72
log-wage_t	-25.56	9.77	-2.62
log-wage_{t-1}	46.77	17.86	2.62

We assume each component follows different $AR(1)$ time-series processes,

$$\begin{aligned} b_t &= \mu_b + \rho_b b_{t-1} + \eta_{bt} \\ \varepsilon_{it} &= \rho_\varepsilon \varepsilon_{it-1} + \eta_{it} \end{aligned} \tag{7}$$

where standard deviations of the innovations η_{bt} and η_{it} are σ_b and σ_ε, respectively. We estimate an equation

$$\pi_{it} = \rho_\varepsilon \pi_{it-1} + \theta k_{it} - \rho_\varepsilon \theta k_{t-1} + b_t - \rho_\varepsilon b_{t-1} + \eta_{it} \tag{8}$$

to which we apply the system GMM of Blundell and Bond (1998). We choose options of two-step efficient estimation with estimated robust standard errors (Windmeijer, 2005; Roodman, 2006). As well as GMM-type instruments π_{it-2}, k_{it-1}, and k_{t-2}, we use current and lagged real values of land capital, both of which seem to be highly correlated with the tangible capital. To capture the effects of the aggregate common shock, we also use current and lagged levels of logged real GDP and current and lagged log-prices of intermediate inputs and labors relative to products price, as well as a comprehensive list of time dummy variables.

Number of observations is 33092 for 1986 to 2007. The profit is defined as real values equal to revenues minus a sum of total cash wages and material amount used. Arellano-Bond (1991) test for $AR(1)$ of the error term shows z-value of 1.48 with the probability values 0.138, that is an acceptance of a null hypothesis of no serial correlation. Hansen J test of overidentifying restrictions and difference-in-Hansen tests of exogeneity of instrument subsets also cannot reject validity of instruments. As Table 2 shows, the estimates of the $AR(1)$ coefficient ρ_ε on the idiosyncratic shock ε_{it} are 0.689(the standard error 0.039). As for the parameter θ in the profit function, the estimates indicate 0.60(S.E. 0.13). The standard deviations of the idiosyncratic shock η_{it} as the residual term in the equation is 0.146.

Next, we recover the aggregate common shock b_t in a way as follows: the productivity a_{it} are calculated with the estimates of a parameter θ in the profit function; and the aggregate shock b_t is the mean of the productivity a_{it} in each

Table 3: Key Parameters in Profit Function (1): the Overall Sample

	Constant(S.E.)	AR(1)(S.E.)	
ε_{it}	-	$\rho_\varepsilon : 0.689(0.039)$	$Std(\eta_{it}) = \sigma_\varepsilon : 0.146$
b_t	1.29(0.81)	$\rho_b : 0.73\ (0.17)$	$Std(\eta_{bt}) = \sigma_b : 0.086$
a_{it}			$Corr(a_{it}, i_{it}) = 0.1376$

year over the plants. We estimate the $AR(1)$ with a constant term process of the aggregate shock using OLS. The $AR(1)$ coefficient ρ_b (the standard error) and the standard deviation of the error term η_{bt} are 0.73 (0.17) and 0.086, respectively. The estimated constant is 1.29(0.81), stochastically insignificant.

The estimated productivity a_{it} is also correlated with investment rates, the correlation coefficient 0.1376. For both $AR(1)$ processes of the productivity shock a_{it}, we apply an approximating method for a first-order Markov process (Tauchen, 1986; Tauchen and Hussey, 1991). The number of aggregate and idiosyncratic states are set equal to 3 and 10, respectively.

3.3 Simulated Method of Moments for Adjustment Cost Functions

Simulated method of moments is applied to our data, where we find a parameter vector $\Theta = (F, \lambda, p_s, \gamma)$ minimizing a weighted distance between empirical and simulated moments as follows:

$$\min_{\Theta} J(\Theta) = \left[\Psi^d - \Psi^S(\Theta)\right]' W \left[\Psi^d - \Psi^S(\Theta)\right] \tag{9}$$

where we assume a parameter p_b set at 1. The procedure is at the first step, given Θ we execute a value function iteration for the Bellman equation (3) or (5). Resulting policy function, at the second step, generates a panel data set of the endogenous variables. At the third step, the panel data obtains $\Psi^S(\Theta)$. Finally, at the fourth step, a minimization of $J(\Theta)$ with some weighting matrix W is done with respect to Θ . The empirical moments we should match with the minimization are inaction rates, two spike rates, positive (higher than 0.2) and negative (lower than -0.2), serial correlation of the investment rates $Corr(i_{it}, i_{it-1})$, and correlation of the investment rates with profitability $Corr(i_{it}, a_{it})$. We also set the annual discount rate β at 0.95 and the annual rate of depreciation δ at 0.08031, a simple average of the rates we used in the perpetual inventory method, 0.073034 for 1986 to 1992 and 0.09593197 for 1993 to 2007. The practical minimization procedure is based on Fackler and Tastan (2008) program code, which provides a general framework for simulation based on indirect inference methodology. We use the Matlab optimization routine *fminsearch* for optimization algorithm.

Table 4: SMM Estimates of the Bellman Equation(1): the Overall Sample

Parameters	Coef.	ASE(t-stat)
F	-0.0063	$0.0079(-0.7952)$
γ	0.0741	0.1296(0.5718)
p_s	1.0168	0.0182(55.9738)
λ	1.0373	0.1657(6.2601)
Moments	Sample	Simulation
$Corr(i_{it}, i_{it-1})$	0.0305	0.4995
$Corr(i_{it}, a_{it})$	0.1376	0.0104
Positive Spike Rate	0.2937	0.1529
Negative Spike Rate	0.00395	0.0111
Inaction Rate	0.069	0

Table 4 indicates coefficients on the adjustment cost parameters, their asymptotic standard errors and the t-statistics. Though the simulated moments are inadequately matched with the sample moments, the parameter estimates suggest a fact that convex adjustment cost is insignificant, fixed costs are none since a parameter F is insignificant and a parameter λ is not different from 1, and irreversibility is also none since $p_s = 1 = p_b$. That is, there are no adjustment costs, neither convex, non-convex nor irreversible.

3.4 Effects of Automobile Electronics on Adjustment Costs

We take some sectoral cases as the samples of plants with embodied technological progress engineered by the automobile electronics. We assume that a sample of the plants benefitting from the auto-electronics might probably possess a different productivity process of A in the profit function $\Pi(A, K)$. Among all the combinations of each products PET, EPS, ABS, AB, WH, LI, or NV, four samples are represented: (PET⌣EPS⌣ABS⌣AB⌣WH⌣LI⌣NV); EPS⌣ABS; EPS⌣ABS⌣WH; and AB⌣LI⌣NV. The number of observations are 10181, 3507, 3534, or 3068, respectively.

Comparing with the coefficients in the benchmark case of the overall sample 2, we state some differences in the estimated parameters ρ_ε, ρ_b and θ seen in 6. In the case of (EPS⌣ABS) or (EPS⌣ABS⌣WH), the estimated parameter θ in the profit function is higher than in the benchmark case, since it is likely that these core technologies of the automobiles are publicly available through the patent acquisitions. So that the plants with the high-tech or permission to use the applicable patents face quite perfect competition in each products market, resulting in higher estimates of θ of physical capital K. In another case of (AB⌣LI⌣NV) or (PET⌣EPS⌣ABS⌣AB⌣WH⌣LI⌣NV) where the Japanese electric companies like the Mitsubishi Electric Corporation gain market share taking advantage of the primary product development, the relatively lower price

Table 5: Summary Statistics (2): Investment Rates in Sectoral Cases

Period: 1986 to 2007	PET⌣EPS⌣ABS ⌣AB⌣WH⌣LI⌣NV	EPS⌣ABS	EPS⌣ABS⌣WH	AB⌣LI⌣NV
Average Investment Rate	0.194	0.182	0.181	0.182
Inaction Rate	0.058	0.049	0.048	0.066
Fraction of Observations with Negative Investment	0.064	0.069	0.069	0.079
Spike Rate: Positive, Higher than 0.2	0.325	0.303	0.304	0.3004
Spike Rate: Negative, Lower than -0.2	0.008	0.0103	0.011	0.0104
Serial Correlation $Corr(i_{it}, i_{it-1})$	0.059	0.0104	0.0105	0.0421
Correlation w/ Profitability $Corr(i_{it}, a_{it})$	0.122	0.184	0.183	0.109

Table 6: System GMM Estimates of Profit Function(2): Sectoral Cases

	PET⌣EPS⌣ABS ⌣AB⌣WH⌣LI⌣NV	EPS⌣ABS	EPS⌣ABS⌣WH	AB⌣LI⌣NV
Variables	Coef. (S.E; Z)			
π_{it-1}	0.62	0.43	0.43	0.599
	$(0.069; 8.94)$	$(0.35; 1.20)$	$(0.45; 0.94)$	$(0.14; 4.29)$
k_{it}	0.48	0.81	0.81	0.25
	$(0.17; 2.76)$	$(0.35; 2.31)$	$(0.46; 1.75)$	$(0.30; 0.82)$
k_{t-1}	-0.22	-0.398	-0.41	0.038
	$(0.18; -1.22)$	$(0.22; -1.83)$	$(0.29; -1.45)$	$(0.28; 0.14)$
log-real GDP$_t$	-37.39	-37.89	-38.95	-39.40
	$(18.75; -1.99)$	$(54.65; -0.69)$	$(66.45; -0.59)$	$(37.18; -1.06)$
log-real GDP$_{t-1}$	37.55	38.09	39.16	39.57
	$(18.76; 2.00)$	$(54.57; 0.70)$	$(66.33; 0.59)$	$(37.22; 1.06)$
log-inter. inputs price$_t$	-52.18	-55.23	-56.67	-53.61
	$(27.51; -1.90)$	$(77.91; -0.71)$	$(94.25; -0.60)$	$(53.74; -1.00)$
log-inter. inputs price$_{t-1}$	-101.29	-107.18	-109.44	-100.58
	$(49.16; -2.06)$	$(150.86; -0.71)$	$(184.30; -0.59)$	$(99.30; -1.01)$
log-wage$_t$	-30.14	-31.76	-32.49	-30.20
	$(15.39; -1.96)$	$(47.17; -0.67)$	$(57.69; -0.56)$	$(30.55; -0.99)$
log-wage$_{t-1}$	55.59	58.83	60.21	55.81
	$(28.19; 1.97)$	$(84.87; 0.69)$	$(103.47; 0.58)$	$(56.05; 1.00)$

Table 7: Key Parameters in Profit Function (2): Sectoral Cases

	Constant(S.E.)	AR(1)(S.E.)	
PET⌣EPS⌣ABS⌣AB⌣WH⌣LI⌣NV			
ε_{it}	-	$\rho_\varepsilon : 0.62(0.069)$	$Std(\eta_{it}) = \sigma_\varepsilon : 0.379$
b_t	1.54(0.93)	$\rho_b : 0.75\ (0.16)$	$Std(\eta_{bt}) = \sigma_b : 0.078$
a_{it}			$Corr(a_{it}, i_{it}) = 0.293$
EPS⌣ABS			
ε_{it}	-	$\rho_\varepsilon : 0.43(0.35)$	$Std(\eta_{it}) = \sigma_\varepsilon : 0.089$
b_t	0.23(0.47)	$\rho_b : 0.92\ (0.19)$	$Std(\eta_{bt}) = \sigma_b : 0.06$
a_{it}			$Corr(a_{it}, i_{it}) = 0.07$
EPS⌣ABS⌣WH			
ε_{it}	-	$\rho_\varepsilon : 0.43(0.45)$	$Std(\eta_{it}) = \sigma_\varepsilon : 0.089$
b_t	0.25(0.42)	$\rho_b : 0.91\ (0.17)$	$Std(\eta_{bt}) = \sigma_b : 0.06$
a_{it}			$Corr(a_{it}, i_{it}) = 0.06$
AB⌣LI⌣NV			
ε_{it}	-	$\rho_\varepsilon : 0.599(0.14)$	$Std(\eta_{it}) = \sigma_\varepsilon : 0.144$
b_t	8.95(0.55)	$\rho_b : -0.03\ (0.06)$	$Std(\eta_{bt}) = \sigma_b : 0.11$
a_{it}			$Corr(a_{it}, i_{it}) = 0.39$

elasticity in the electric product markets leads to lower or insignificant coefficients of the parameter θ.

As for the $AR(1)$ parameters ρ_ε and ρ_b of the idiosyncratic/ aggregate productivities, the core automobile technologies have a tendency of none serial correlations in the idiosyncratic ingredient but high serial correlations in the aggregate one. In contrast, the electric products have a little lower serial correlation in the idiosyncratic productivities, with the aggregate ones remaining almost the same.

Table 8 shows our SMM estimates. For the sectoral cases, we have to see some anomalous results. Note that, among the 7 time-products dummies, the correlation ratios η between the dummy variables and the productivity estimates a_{it} suggest the variables EPS and ABS are appropriate for identifying the auto-electronics effects. Based on the appropriateness, we give more priority to cases of (EPS⌣ABS) and (EPS⌣ABS⌣WH). Table 8 indicates that the effects of automobile electronics are mixed, if any. For the overall sample of the auto-parts suppliers, there are no adjustment costs in any form, neither convex, non-convex nor irreversible. As for the sectoral plants where the automobile electronics seems embodied in the tangible capitals, we clearly detect a significant existence of the convex adjustment costs. Regarding another type of the adjustment costs, on one hand, the sell price of the used capitals is anomalously higher than the buy price, which means the auto-electronics makes investment decision reversible. On the other hand, the fixed costs of plant restructuring, worker retraining or organizational restructuring emerge, especially in a form of costs proportional to a plant size rather than an opportunity cost of investment.

Table 8: SMM Estimates of the Bellman Equation(2): Sectoral Cases

	PET∪EPS∪ABS ∪AB∪WH∪LI∪NV	EPS∪ABS	EPS∪ABS∪WH	AB∪LI∪NV
Parameters	Coef. (A.S.E; t-stat)			
F	-0.02357	0.0071	0.0073	-0.02196
	$(0.000057; -411.86)$	$(0.0047; 1.508)$	$(0.000026; 277.078)$	$(0.000000; -\inf)$
γ	0.1769	0.0676	0.0720	0.1667
	$(0.000066; 2692.82)$	$(2.556; 0.026)$	$(0.000000; \inf)$	$(0.000000; \inf)$
p_s	-0.769	1.0104	1.0118	-1.3163
	$(0.0000; -\inf)$	$(0.564; 1.791)$	$(0.00027; 3713.86)$	$(0.000000; -\inf)$
λ	0.8669	1.1759	1.1328	1.4173
	$(0.000066; 13192.43)$	$(2.174; 0.541)$	$(0.000000; \inf)$	$(0.000000; \inf)$
Moments	Simulation (Sample)			
$Corr(i_{it}, i_{it-1})$	0.8060	0.9972	0.9966	0.9873
	(0.059)	(0.0104)	(0.0105)	(0.0421)
$Corr(i_{it}, a_{it})$	0.0001	-0.0006	0.0037	0.0030
	(0.122)	(0.184)	(0.183)	(0.109)
Positive Spike Rate	0.0260	0.1522	0.1346	0.0000
	(0.325)	(0.303)	(0.304)	(0.3004)
Negative Spike Rate	0	0.0227	0.0181	0
	(0.008)	(0.0103)	(0.011)	(0.0104)
Inaction Rate	0.0896	0	0.0548	0
	(0.058)	(0.049)	(0.048)	(0.066)

4 Conclusion

In the face of the automobile electronics developments, what types of capital adjustment cost did the automobile electronics raise in the auto-parts suppliers? We conjectured that the GPT requires the auto-parts suppliers to learn by doing capital-embodied technological progress. We explored quantitatively the effects of the automobile electronics on capital adjustment costs, either convex, non-convex or irreversible functions. Following Cooper and Haltiwanger (2006), we estimated via simulated method of moments the Bellman equations for plants' dynamic optimization with respect to tangible capital, where there are decisions of inaction, buy or sell capitals to choose discretely.

Though our estimates show a lack of stability in the coefficients, the effects of automobile electronics are mixed, if any. For the overall sample of the auto-parts suppliers, there are no adjustment costs in any form, neither convex, non-convex nor irreversible. As for the sectoral plants where the automobile electronics seems embodied in the tangible capitals, we clearly detect a significant existence of the convex adjustment costs. Regarding another type of the adjustment costs, on one hand, the sell price of the used capitals is anomalously higher than the buy price, which means the auto-electronics makes investment decision reversible. On the other hand, the fixed costs of plant restructuring, worker retraining or organizational restructuring emerge, especially in a form of costs proportional to a plant size rather than an opportunity cost of investment. The nature of adjustment costs associated with the auto-electronics implies economic policy measures which should be taken in order to compensate for the output losses from the capital adjustment costs in the face of general purpose technologies.

References

[1] Arellano, M., and S. Bond, 1991. "Some Tests of Specification for Panel Data: Monte Carlo Evidence and an Application to Employment Equations." *Review of Economic Studies*, vol. 58(2), pp. 277-97.

[2] Bloom N., M. Schankerman and J. Van Reenen, 2007. "Identifying Technology Spillovers and Product Market Rivalry," NBER Working Papers #13060.

[3] Blundell, R. and S. Bond. 1998. "Initial Conditions and Moment Restrictions in Dynamic Panel Data Models." *Journal of Econometrics*, 87(1), pp. 115-143.

[4] Bresnahan, T., and M. Trajtenberg. 1996. "General Purpose Technologies: 'Engines of Growth'?" *Journal of Econometrics, Annals of Econometrics* 65, pp. 83-108.

[5] Christiano, L., M. Eichenbaum, and C. Evans. 2005. “Nominal Rigidities and the Dynamic Effects of a Shock to Monetary Policy.” *Journal of Political Economy* vol. 113(1), pp. 1-45.

[6] Cooper, R., and J. Ejarque. 2003. "Financial Frictions and Investment: Requiem in Q." *Review of Economic Dynamics*, 6, pp. 710-28.

[7] Cooper, R., and J. Haltiwanger. 2006. "On the Nature of Capital Adjustment Costs." *Review of Economic Studies*, 73, pp. 611-33.

[8] David, P. 1990. "The Dynamo and the Computer: An Historical Perspective on the Modern Productivity Paradox." *American Economic Review*, 80(2), pp. 355-61.

[9] Eberly, J., S. Rebelo, and N. Vincent, 2006, "Investment and Value: A Neoclassical Benchmark." NBER working paper #13866.

[10] Fackler, P., and H. Tastan, 2008. "A Framework for Indirect Inference." Mimeo.

[11] Greenwood, J., Z. Hercowitz, and P. Krusell, 1997. "Long-Run Implications of Investment-Specific Technological Change." *American Economic Review*, vol. 87(3), pp. 342-62.

[12] Griffith, R., R. Harrison, and J. Van Reenen, 2006. "How Special is the Special Relationship? Using the Impact of US R&D Spillovers on UK Firms as a Test of Technology Sourcing." *American Economic Review*, vol. 96(5). pp. 1859-1875.

[13] Griliches, Z. 1990. “Patent Statistics as Economic Indicators: A Survey,” *Journal of Economic Literature* XXVIII: 1661-1707

[14] Hayashi, F., 1982. "Tobin’s Marginal q and Average q: A Neoclassical Interpretation." *Econometrica*, vol. 50(1), pp. 213-24.

[15] Hornstein, A. and P. Krusell, 1996. "Can Technology Improvements Cause Productivity Slowdowns?," NBER Chapters, in: *NBER Macroeconomics Annual 1996*, Volume 11, pp. 209-76.

[16] Jovanovic, B., and P. Rousseau. 2005. "General Purpose Technologies." Chapter 18 in *Handbook of Economic Growth*. vol. 1B, edited by P. Aghion and S. Durlauf, Elsevier B.V.

[17] Justiniano, A., and G. Primiceri, 2008. "The Time-Varying Volatility of Macroeconomic Fluctuations." *American Economic Review*, vol. 98(3), pp. 604-41.

[18] Penrose, E., 1959. *The Theory of the Growth of the Firm*. New York: John Wiley.

[19] Tauchen, G. 1986. "Finite State Markov-Chain Approximations to Univariate and Vector Autoregressions." *Economics Letters*, 20, pp. 177-81.

[20] Tauchen, G., and R. Hussey, 1991. "Quadrature-Based Methods for Obtaining Approximate Solutions to Nonlinear Asset Pricing Models." *Econometrica*, vol. 59(2), pp. 371-96.

[21] Tokuda, A., and Y. Saeki. 2007a. "The Automobile Electronics (1): A Market Analysis of In-Vehicle Electronically-Controlled System."(in Japanese) *Ritsumeikan Business Journal*, 46(2), pp. 85-102.

[22] Tokuda, A., and Y. Saeki. 2007b. "The Automobile Electronics (2): A Market Analysis of In-Vehicle Electronically-Controlled System."(in Japanese) *Ritsumeikan Business Journal*, 46(3), pp. 55-90.

[23] Tokuda, A., and Y. Saeki. 2007c. "The Automobile Electronics (3): A Market Analysis of In-Vehicle Electronically-Controlled System."(in Japanese) *Ritsumeikan Business Journal*, 46(4), pp. 239-76.

[24] Tonogi, K., J. Nakamura, and K. Asako. 2010. "Estimation of Multiple q Models of Investment: Investment Behavior over Heterogeneous Capital Goods during the Period of Excess Capacity Reduction."(in Japanese) *Economics Today*, No. 31(2), Research Institute of Capital Formation, Development Bank of Japan.

[25] Uzawa, H, 1969. "Time Preference and the Penrose Effect in a Two-Class Model of Economic Growth." *Journal of Political Economy*, vol. 77(4), pp. 628-52.

[26] YANO Research, 2009. "In-vehicle Semiconductor Market 2009 to 2010"(in Japanese).

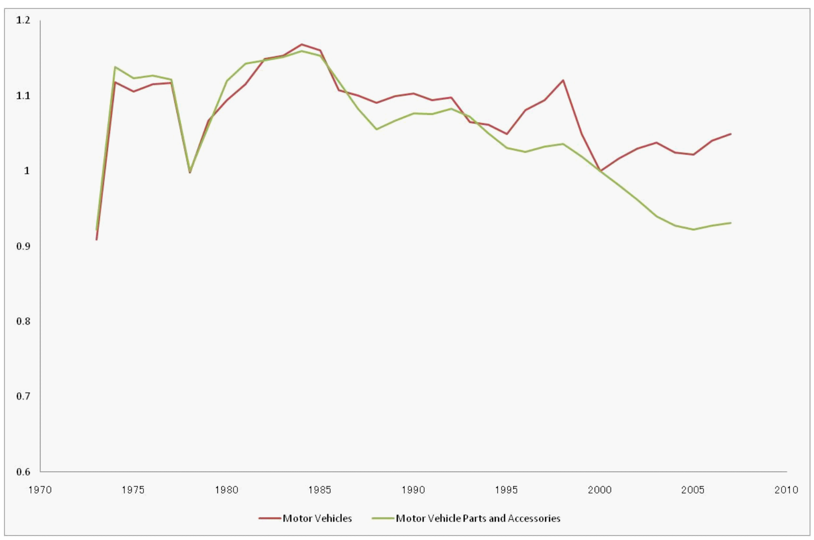

Figure 1: Market Prices of Motor Vehicles and Motor Vehicle Parts and Accessories; 1 in 2000; Source: *The Japan Industrial Productivity Database 2010 (JIP Database 2010)*.

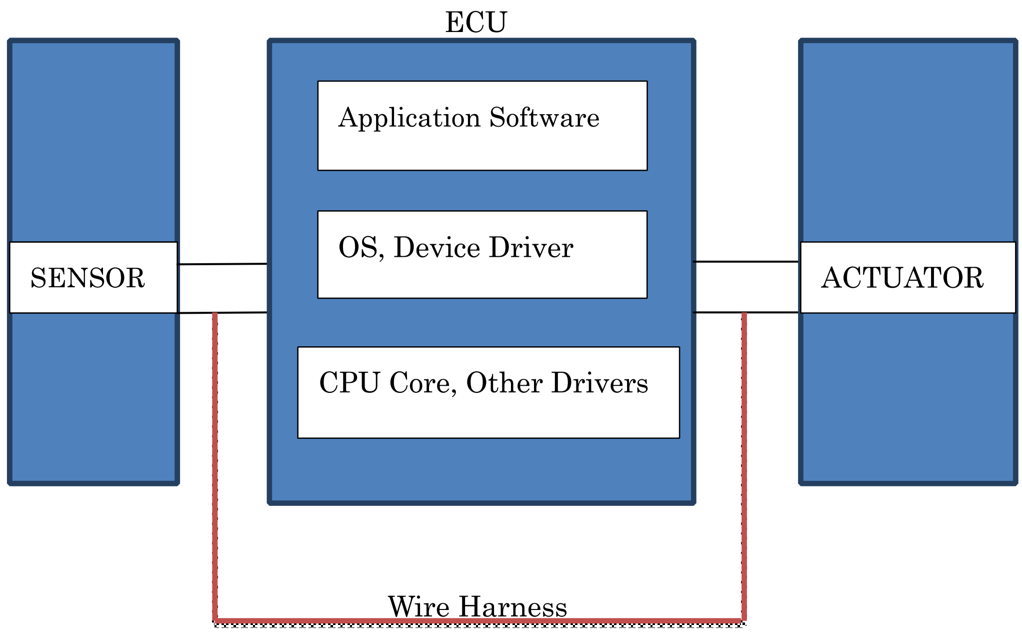

Figure 2: Automobile Electronics; Source: Figure 2-1 in Tokuda and Saeki (2007b).

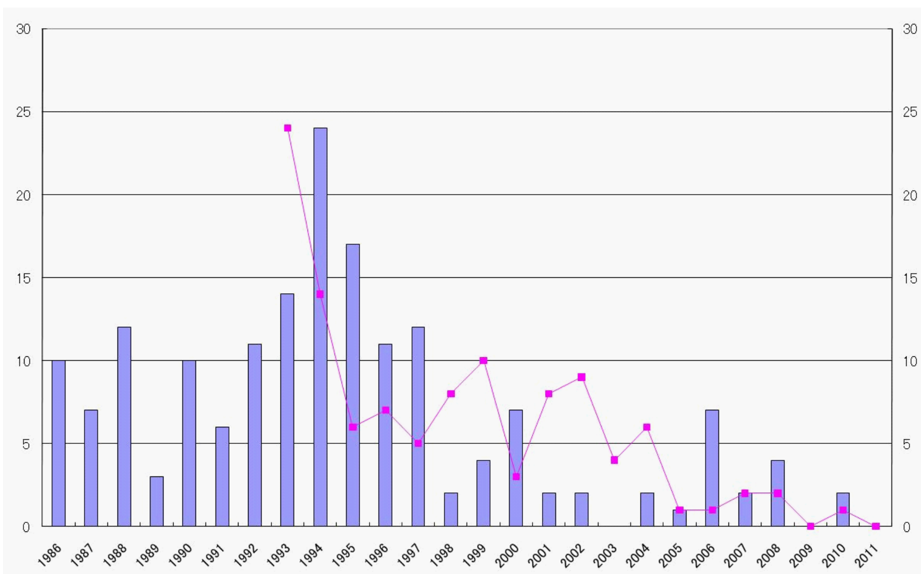

Figure 3: The Number of Patent Acquisitions (Vertical Bar; Left Axis) and Applications (Solid Line; Right Axis), as of July 8, 2011: Electronically-Controlled Fuel Injection Device (PET); Source: *Industrial Property Digital Library.*

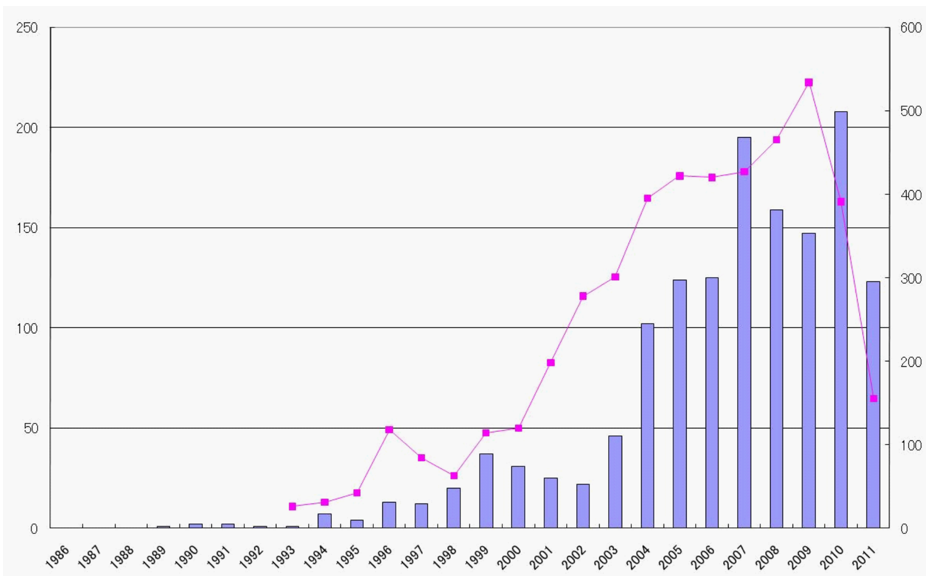

Figure 4: The Number of Patent Acquisitions (Vertical Bar; Left Axis) and Applications (Solid Line; Right Axis), as of July 8, 2011: Electric Power Steering (EPS); Source: *Industrial Property Digital Library.*

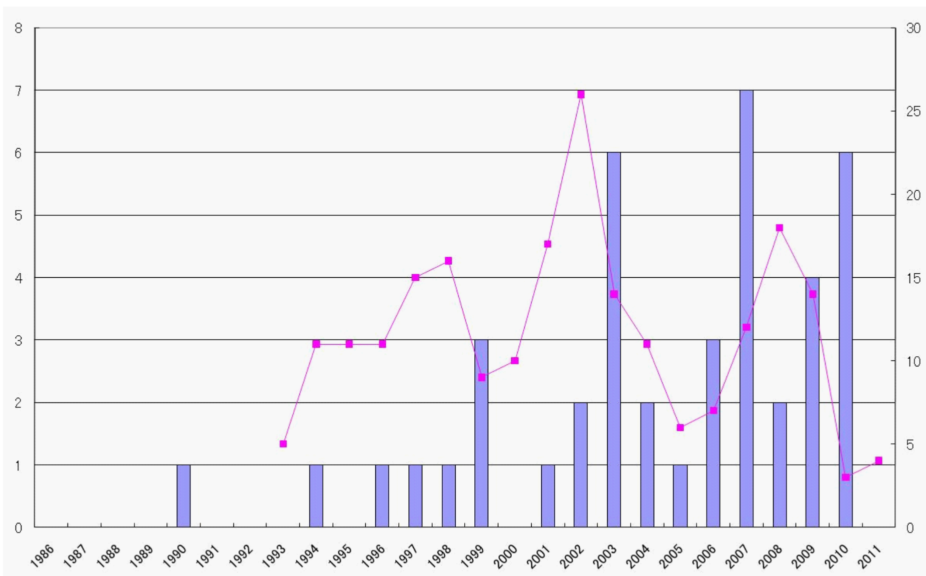

Figure 5: The Number of Patent Acquisitions (Vertical Bar; Left Axis) and Applications (Solid Line; Right Axis), as of July 8, 2011: Anti-Lock Brake System (ABS); Source: *Industrial Property Digital Library.*

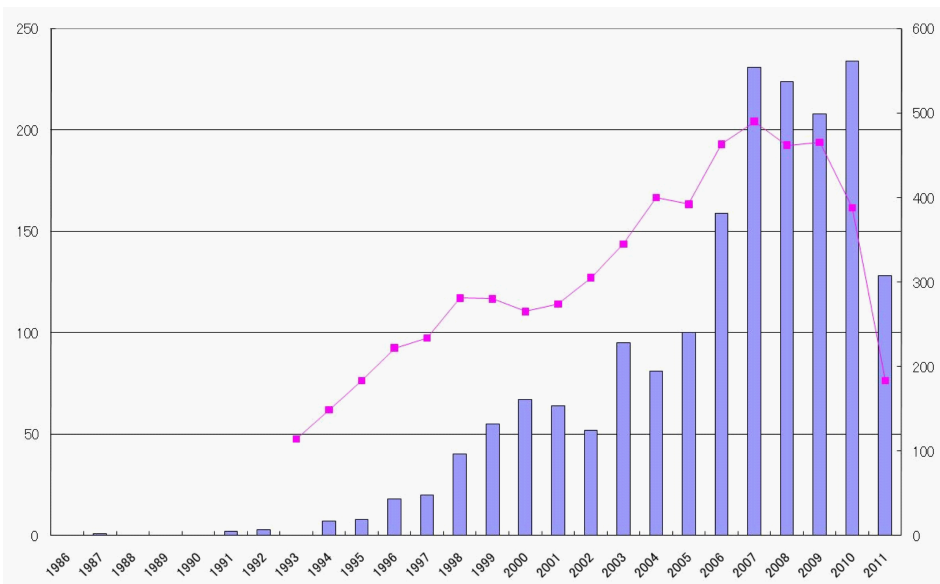

Figure 6: The Number of Patent Acquisitions (Vertical Bar; Left Axis) and Applications (Solid Line; Right Axis), as of July 8, 2011: Airbag; Source: *Industrial Property Digital Library.*

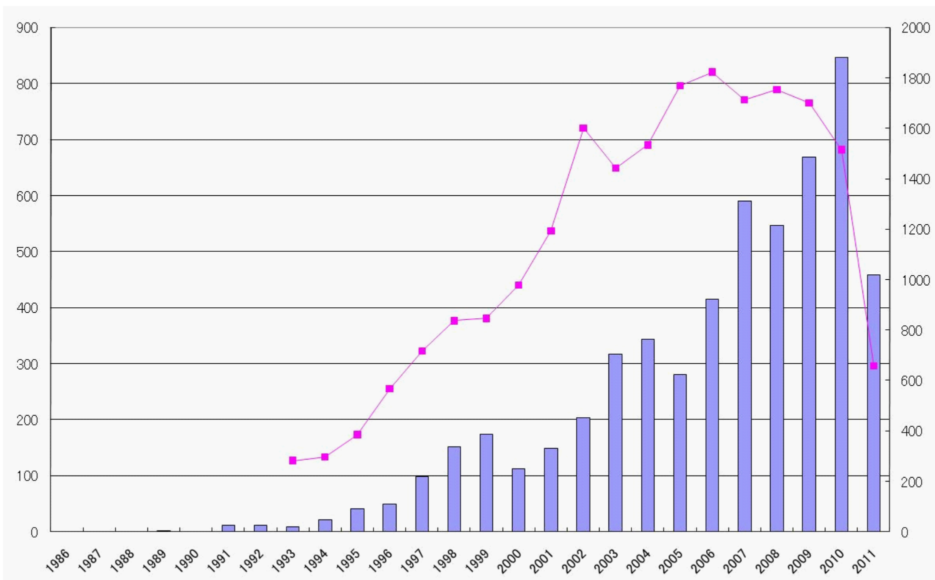

Figure 7: The Number of Patent Acquisitions (Vertical Bar; Left Axis) and Applications (Solid Line; Right Axis), as of July 8, 2011: Navigation System; Source: *Industrial Property Digital Library.*

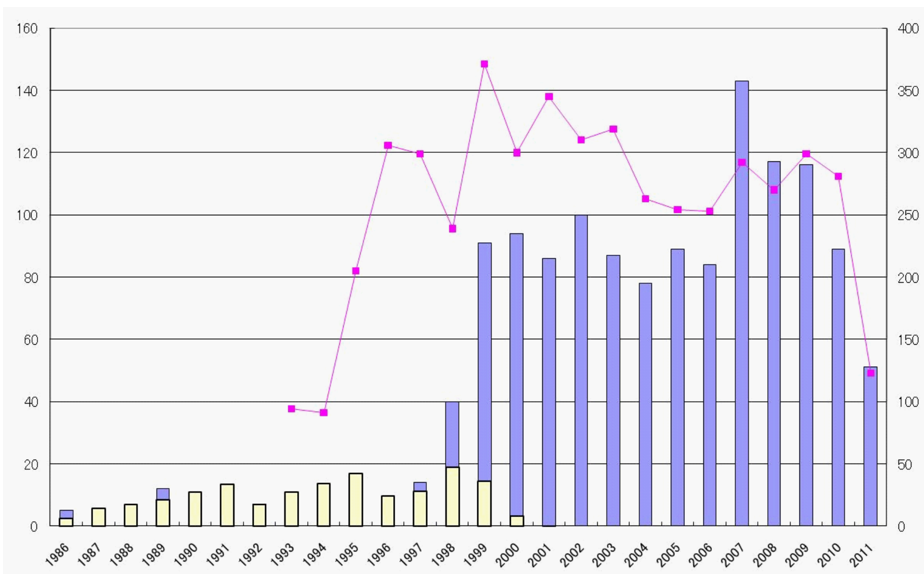

Figure 8: The Number of Patent Acquisitions (Vertical Bar; Left Axis) and Applications (Solid Line; Right Axis), as of July 8, 2011: Wire Harness; Source: *Industrial Property Digital Library.*

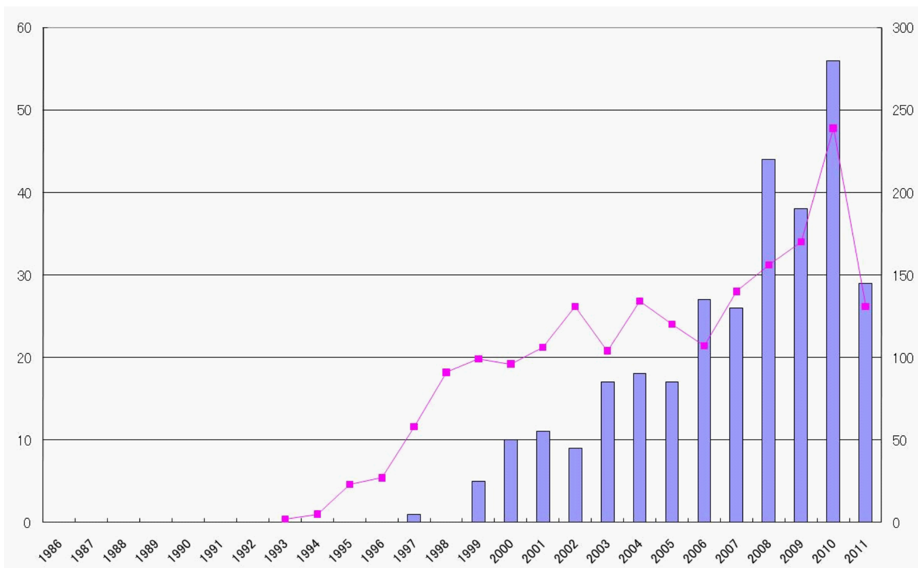

Figure 9: The Number of Patent Acquisitions (Vertical Bar; Left Axis) and Applications (Solid Line; Right Axis), as of July 8, 2011: Lithium-Ion Battery; Source: *Industrial Property Digital Library.*