PRICE CHANGES, MAINTENANCE, AND THE RATE OF DEPRECIATION

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Abstract—This study estimates rates of deterioration and depreciation for a sample of used privately owned single- and twin-engine aircraft over the period 1971–1991. The adoption of a strict liability standard in the 1970s lead to a 775% increase in liability expenses for the manufacturers of private planes between 1977 and 1985, resulting in sharp increases in the prices of new and used planes throughout the late 1970s and 1980s. This period of rapid price inflation coincides with a decrease in the depreciation rates for used single- and twin-engine aircraft after 1975. In addition, our results indicate that the rate of deterioration is positively related to the required cost of engine maintenance. These findings call into question the commonly invoked assumption that depreciation rates may be treated as exogenously determined constants, and lend support to the hypothesis that deterioration and depreciation rates respond systematically to key economic variables.

I. Introduction

ASSUMPTIONS regarding the rate at which assets depreciate play an important role in many different areas of applied economics. For example, the construction of an aggregate stock of capital, or the user cost of capital, both require information about the rate at which assets of a given age depreciate.1 A great deal of simplification may be achieved if assets are assumed to depreciate at a geometric rate that is stable over time. Although commonly invoked, the implications of this assumption are somewhat severe. In terms of the prices of used autos, for example, the assumption of a constant geometric rate of depreciation requires (1) the annual percentage decrease in the price of a one-year-old car to be the same as that of a five- or ten-year-old car, and (2) the rate of depreciation to be constant over time, and independent of economic factors, such as the price of new and used cars, maintenance and fuel costs, interest rates, taxes, etc.

Empirical support for the assumption of a geometric rate of depreciation has been reported in a number of previous studies. Using the pioneering approach developed by Hall (1971),2 Ramm (1970), Wykoff (1970, 1989), Ohta and Griliches (1976), Hulten and Wykoff (1980, 1981a,b), and Hulten et al. (1989), among others, have either reported that depreciation occurs at a constant geometric rate, or concluded, like Hall (1971, p. 258), that “while depreciation is almost certainly not geometric, the geometric function is probably a reasonable approximation for many purposes.”3 The hypothesis that depreciation rates are stable over time has also been the subject of numerous empirical tests. Studies by Griliches (1970), Wykoff (1970), Ramm (1970), and Cagan (1971) all reported rates of depreciation that varied over time, whereas the work of Hulten and Wykoff (1981b) supported the assumption of time-invariant depreciation rates. Hulten et al. (1989) estimated age–price profiles for machine tools and construction equipment to test the hypothesis that rising energy costs after 1973 reduced the value of used energy-intensive assets. They concluded (p. 255):

We have found that a major event like the energy crises, which had the potential of significantly increasing the rate of obsolescence, did not in fact result in a systematic change in age–price profiles. This lends confidence to procedures that assume stationarity in order to achieve a major degree of simplification (and because nonstationarity is so difficult to deal with empirically). Or, put simply, the use of a single number to characterize the process of depreciation (of a given type of capital asset) seems justified in light of the results. . .

The purpose of this paper is to reexamine the hypothesis that assets depreciate at a geometric rate that is stable over time. The literature on optimal asset durability developed by Feldstein and Rothschild (1974), Schmalensee (1974), and Parks (1979) indicates that the rate of deterioration responds systematically to changes in the expected price of the asset and the cost of maintenance.4 These hypotheses are tested using data for used single-engine and twin-engine privately owned aircraft in the United States over the period of 1970–1991. The adoption of a strict liability standard in the 1970s lead to a 775% increase in liability expenses for the manufacturers of private planes between 1977 and 1985, resulting in sharp increases in the prices of new and used planes throughout the late 1970s and 1980s. This period of rapid price inflation coincides with a decrease in the rates of depreciation and deterioration for used single-engine and twin-engine aircraft after 1975. In addition, our results indicate that the rates of depreciation and deterioration are not geometric, although the use of a geometric rate would provide a reasonable approximation at a given point in time.

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1 See Berndt (1991, chap. 6) for a clear discussion of the role of the rate of depreciation in defining an aggregate stock of capital and the user cost of capital.

2 See Hulten and Wykoff (1981a) for a review of the empirical literature on depreciation.

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Finally, our results indicate that the rate of deterioration is positively related to the required cost of engine maintenance. These findings lend support to the use of models that treat the rate of depreciation as an endogenous variable.

II. Theoretical Considerations

Depreciation may be measured using data on used asset prices. Define \( P(s, t) \) to be the price of an asset of age \( s \) observed in year \( t \). The price of the asset may change over time as the result of three distinct forces: inflation, obsolescence, and deterioration. The total change in the price of the asset over time may be written as

\[
\Delta P = P(s, t) - P(s + 1, t + 1).
\]

By inserting the term \( P(s + 1, t) \), equation (1) may be rewritten as

\[
\Delta P = [P(s, t) - P(s + 1, t)]
- [P(s + 1, t + 1) - P(s + 1, t)].
\]

The term in the first set of brackets is defined to be depreciation (\( DEP \)), the change in the price of the asset resulting from a change in age, holding time constant. The term in the second set of brackets represents asset inflation, the change in the price of an asset of a given age over time.

Define the vintage of an asset to be \( v = t - s \). The depreciation term may thus be written as

\[
DEP = [P(v, s, t) - P(v + 1, s + 1, t)].
\]

The introduction of the vintage index illustrates that depreciation is the result of two separate forces: (1) an increase in age from \( s \) to \( s + 1 \), and (2) an increase in vintage from \( v \) to \( v + 1 \). It is possible to separate the combined effects of the change in age and vintage by inserting the term \( P(v, s + 1, t) \) into equation (3) to obtain

\[
DEP = [P(v, s, t) - P(v + 1, s + 1, t)]
+ [P(v, s + 1, t) - P(v + 1, s + 1, t)].
\]

The term in the first set of brackets is defined as deterioration, the change in the price of an asset resulting from a change in age, holding vintage and time constant. Deterioration represents the combined effects of the reduction in the useful life of the asset, input decay (an increase in the input requirements necessary to maintain a given level of output), and output decay (the reduction in the output produced by a given asset, holding other inputs constant). The term in the second set of brackets represents obsolescence, the change in the price of an asset resulting from a change in vintage, holding age and time constant. Obsolescence refers to the decline in the value of used assets resulting from technological improvements embodied in new assets.

The owner of a used asset has no control over the rate at which technological improvements are embodied in new assets, and thus has little, if any, control over the rate of obsolescence. Several authors, however, have developed models in which the rate of deterioration is treated as an endogenous variable. Feldstein and Rothschild (1974) developed a model in which the firm is assumed to select the level of machine durability that will minimize the discounted cost of providing a unit of capital services forever. Their results indicated that planned durability is a function of interest rate and taxes. In addition, they argued that unanticipated increases in machine prices would cause a postponement in replacement investment, which in turn should lead to an increase in the lives of used equipment, thus reducing the rate of deterioration. Schmalensee (1974) developed a model in which the rate of asset deterioration is a function of durability characteristics chosen at the time of manufacture and maintenance expenditures. Schmalensee demonstrated that an increase in the purchase price of the good will lead to an increase in maintenance expenditures, reducing the rate of capital deterioration.

Parks (1979) extended Schmalensee’s model to explore the effect of changes in asset prices and the cost of maintenance on the rate of deterioration. In Parks’ model, firms are assumed to offer a range of durable assets that differ in the level of durability \( \delta_v \), which is assumed to be fixed at the time of manufacture \( v \). Consumers are assumed to select the level of maintenance \( \varphi_v(t) \) that will minimize the rental price of the asset. The level of maintenance may be changed after the date of manufacture, and thus may be determined at any point in time \( t \). The flow of services provided by the asset is assumed to deteriorate with respect to age at a rate \( \lambda(\delta_v, \varphi_v(t)) \), which is assumed to be a convex function with \( \lambda_0 < 0 \) and \( \lambda_1 < 0 \).

The rental price of an asset of vintage \( v \) in time \( t \) is given by

\[
p_v(t) = rP_v(t) + \lambda(\delta_v, \varphi_v(t))P_v(t + 1)
+ [P_v(t) - P_v(t + 1)] + c(t)\varphi_v(t)
\]

where \( P_v(t) \) is the purchase price of an asset of vintage \( v \) in time \( t \), \( c(t) \) is the cost of a unit of maintenance in time \( t \), and \( r \) is the interest rate. The terms in equation (5) represent the opportunity cost of holding the asset for 1 year, the cost associated with deterioration of the asset, capital gains or losses, and the cost of maintenance, respectively. Consumers are assumed to choose the level of \( \varphi_v(t) \) to minimize the rental price, requiring that

\[
\frac{\partial p_v(t)/\partial \varphi_v(t)}{\varphi_v(t)} = P_v(t + 1)\lambda(\delta_v, \varphi_v(t)) + c(t) = 0.
\]

See Feldstein and Rothschild (1974) or Wykoff (1989) for further discussion of input and output decay.

\[6\] It may be possible to influence the effects of obsolescence by purchasing assets that may be retrofitted to reflect changes in technology. For example, one may reduce the rate of obsolescence for personal computers by purchasing a machine with an upgradable microprocessor.
Define $\varphi_v(\delta_v, c(t), P_v(t+1))$ to be the level of maintenance that satisfies equation (6). The effect of a change in the cost of maintenance on the optimal level of maintenance is given by

$$\frac{\partial \varphi_v}{\partial c(t)} = -1/P_v(t+1) \lambda_{ve} < 0. \quad (7)$$

Given that $\lambda_e < 0$, an increase in maintenance costs will reduce the level of maintenance, increasing the rate of deterioration. The effect of a change in the expected future price of the asset on the optimal level of maintenance is given by

$$\frac{\partial \varphi_v(t)}{\partial P_d(t+1)} = -\lambda_v/P_d(t+1) \lambda_{ve} > 0. \quad (8)$$

Given that $\lambda_e < 0$, an increase in the expected future price of the asset will lead consumers to increase the level of maintenance efforts, reducing the rate of deterioration.

Two empirically testable hypotheses thus emerge from Parks' model. First, an increase in the expected future price of the asset will lead consumers to increase maintenance, thus reducing the rate of deterioration. Second, an increase in the price of maintenance will lead consumers to reduce maintenance, thus increasing the rate of deterioration. Since deterioration is a component of depreciation, it is expected that the rate of depreciation will respond in a similar manner to changes in the expected future price of the asset and the cost of maintenance.

### III. Industry Background

To test the hypotheses discussed above, we examine a sample of general aviation (GA) aircraft in the United States, which covers all aircraft with the exception of commercial air carriers. In 1990 the fixed-winged GA fleet in the United States totaled 245,360 aircraft, of which 95.4% employ piston engines. We focus on single-engine and twin-engine piston aircraft, which comprise 84.52% and 10.80%, respectively, of the entire GA fleet.

Beginning in 1963 the legal system in the United States began a gradual transition to a strict liability standard. Under strict liability a manufacturer of a product found to be defective or unreasonably dangerous when put to its intended use may be held liable without proof of negligence or fault. Although roughly 77% of all GA accidents are attributed to pilot error, the liability expenses of GA manufacturers increased significantly throughout the late 1970s and 1980s as a result of the change in liability standards. Total industry liability expenses in 1977 were estimated to be $24 million (Sontag 1987), implying a liability expense per new plane of $1420. In 1986 Piper and Beech estimated that liability insurance costs added $75,000 to $80,000 to the price of each new plane (Priest (1991)).

The financial impact of the strict liability standard was magnified by the long service lives of GA aircraft. In 1990 the average age of a GA plane was 23.8 years, implying a large stock of existing aircraft from which liability suits could arise. Manufacturers increased the prices of new planes in an effort to cover the expected liability costs associated with current sales, and to cover the liability costs resulting from previous sales. The average price of new single- and twin-engine planes described in the sample below increased at an annual average rate of 3.93% and 3.89%, respectively, between 1960 and 1975; this rate of price increase accelerated to 12.64% and 10.95%, respectively, for the period of 1975–1990. Similar rates of price increase for single-engine (13.76%) and twin-engine (10.29%) aircraft were obtained by dividing the total value of single- and twin-engine planes sold by the number of planes sold for the period of 1975–1985 (GAMA (1990)).

Not surprisingly, the sales of new planes declined from an average of 12,159 units per year between 1965 and 1975 to 1021 planes in 1991.

If consumers consider used planes to be substitutes for new planes, the increase in new plane prices would increase the demand for, and ultimately the price, of used aircraft. To the extent that the owners of used aircraft become subject to the expanded liability, however, the increased liability exposure will reduce the demand for used planes. The potential impacts of expanded liability on demand should be greater for twin-engine planes than for single-engine planes, as more of the former are employed for commercial purposes. The differential impacts of expanded liability are consistent with the fact that the average price of single-engine used planes less than 5 years old increased by 437.65% between 1971 and 1985, whereas the prices of used twin-engine aircraft increased by 228.9% over the same period. This pattern of price increases is also consistent, however, with the fact that the prices of new twin-engine aircraft increased by a smaller percentage than the prices of new single-engine planes during this period.

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9 The liability expenses associated with previously sold aircraft constitute a fixed expense, and thus do not affect the firm’s marginal cost of current aircraft. For this reason one would expect the liability costs for previously sold aircraft to have no impact on the price of new aircraft. As Viscusi (1991, pp. 39–40) argues, however, manufacturers attempted to pass on the liability costs for past sales to new consumers: “A fundamental miscalculation by the industry has been the assumption that the liability costs for planes already sold can be recouped in today’s marketplace. The price of planes sold in an earlier liability era did not fully reflect their ultimate liability costs. Firms should treat these unanticipated liability costs as sunk costs. Efforts to price new planes to cover past liability costs cannot succeed, because current consumers do not benefit from a liability price tag that includes not only their own prospective liability costs but also a share of earlier awards.”

10 Any liability exposure experienced by aircraft owners is probably positively correlated with the age of the plane. As a result, the change in liability rules would reduce the prices of older planes relative to the prices of newer planes. Such a change in relative prices would result in an increase in the rate of depreciation or deterioration, not a decrease.
Manufacturers may have responded to the liability crisis by improving the quality of the planes, thus accounting (at least in part) for the rapid price increases. The fatal accident rate for GA aircraft declined over the period of 1970–1989, but at a slower rate than over the period of 1950–1969 (Martin (1991)). In addition, hedonic price regressions employing new-plane price data and the performance attribute variables discussed below were estimated separately for single- and twin-engine planes. The price indexes based on the hedonic regressions indicate that quality-adjusted prices increased at an annual average rate of 3.54% and 3.75% for single-engine and twin-engine aircraft, respectively, during 1960–1975; the corresponding estimates for 1975–1990 are 9.17% and 9.63%. Increases in the quality of GA aircraft after 1975 thus do not appear to be responsible for the rapid rate of price increase after 1975.

IV. Data

The data employed in this study were obtained from the spring editions of the Aircraft Bluebook Price Digest for the years 1971, 1975, 1980, 1985, and 1991. The Bluebook contains average retail prices of used aircraft, as reported to the publishers by aircraft dealers, appraisers, and insurers, together with aircraft specification and performance data. In some cases it was necessary to refer to the Used Aircraft Guide to obtain performance data not reported in the Bluebook.

Within a given class of aircraft there are wide variations in price and performance across manufacturers and models, and frequent changes in specifications and performance for a given model over time. The price of a used plane is assumed to be a function of engine horsepower ($HP$), maximum speed ($SPEED$), standard fuel capacity ($FUEL$), carrying capacity measured in pounds ($CARRY$), all engine service ceiling ($CEILING$), and a dummy variable defined as $PRESS = 1$ if the cabin is pressurized, and 0 otherwise. In addition, the single-engine equation contains a dummy variable defined as $RETRACT = 1$ if the plane has retractable landing gear, and 0 otherwise. Sample means are reported in Table 1. All of these variables are expected to have a positive impact on used plane prices. In addition, firm dummy variables are included for “make effects” across manufacturers.

Engine manufacturers establish a TBO (time between overhaul) for each engine model, which represents the recommended number of hours that an engine may be operated before being overhauled. The FAA recommends, but does not require, that owners follow the TBO in determining when to overhaul an engine. The Bluebook reports the TBO, and the average field cost of overhauling a given engine for each plane. Dividing the TBO into the average cost of an overhaul yields $MAINT$, the maintenance cost per hour of engine use. Ex post, maintenance costs will vary from plane to plane, and pilot to pilot, depending on operating conditions, the operator’s risk preferences, etc. We assume, however, that owners base their willingness to pay for used aircraft on their ex ante estimate of maintenance costs, which presumably are based on the published data available at the time of purchase, including the TBO and the average cost of an overhaul. $MAINT$ is assumed to have a negative impact on the price of a used plane, but is expected to have a positive impact on the estimated rates of depreciation and deterioration.

Estimates of the rate of depreciation or deterioration based on used asset prices may be biased if planes of a given cohort are retired at different points in time. If this is the case, the price of the planes still in use in year $t$ represents the average price of the survivors, and not the average price of the planes in the original cohort. Failure to control for the nonsurvivors will thus lead to the use of average prices that overstate the value of the original cohort, resulting in possibly biased estimates of the rate of depreciation and deterioration. To correct for the retirement bias Hulten and Wykoff (1981a,b) employ a weighted average of the price of the survivors and the nonsurvivors, where the weights represent the probabilities of surviving and not surviving.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Single-Engine Aircraft</th>
<th>Twin-Engine Aircraft</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRICE</td>
<td>$30,091</td>
<td>$64,482</td>
</tr>
<tr>
<td>MAINT</td>
<td>$4.29</td>
<td>$8.36</td>
</tr>
<tr>
<td>HP</td>
<td>208.20</td>
<td>278.56</td>
</tr>
<tr>
<td>SPEED</td>
<td>165.95</td>
<td>237.01</td>
</tr>
<tr>
<td>FUEL</td>
<td>54.82</td>
<td>134.56</td>
</tr>
<tr>
<td>CARRY</td>
<td>1101.4</td>
<td>2168.8</td>
</tr>
<tr>
<td>CEILING</td>
<td>16,429</td>
<td>22,607</td>
</tr>
<tr>
<td>N</td>
<td>2453</td>
<td>1088</td>
</tr>
</tbody>
</table>

13 Engine manufacturers have an incentive to extend the TBO, on the assumption that aircraft owners prefer engines that require infrequent maintenance, all else being equal. On the other hand, manufacturers will have an incentive to minimize the TBO in an effort to minimize their liability resulting from engine failures. In addition, aircraft manufacturers profit from a shorter TBO because they frequently sell the replacement parts used during the overhaul. Presumably engine manufacturers select the TBO that will maximize expected profits, which may not be optimal from the owner’s point of view in terms of minimizing expected maintenance costs. The average TBO has increased over time for the planes in our sample. This may reflect the effects of technical change that has extended engine durability, or the fact that plane manufacturers terminated the production of low-cost planes which employed older vintage engines that require more maintenance.

14 See Hulten and Wykoff (1981a,b) and Wykoff (1989) for further discussion of the effects of differential retirement ages on the estimated rate of depreciation.

15 By definition the average weighted price is less than the average price of the survivors if the survival ratio is less than 1. Since the survival ratio is inversely related to age, the difference between the two is an increasing function of age. As a result, the estimated rates of deterioration and depreciation obtained using the average weighted prices should exceed the estimated rates obtained using the average prices of the survivors.

11 Aircraft dealers who subscribe to the Bluebook are asked quarterly to fill out a “help sheet,” listing the make, model, year of manufacture, and other information for every transaction involving a used plane. In addition, they are asked for the price they paid for the plane or the price at which they sold the plane. This information is then tabulated by the editors of the Bluebook to arrive at an average retail price for a given plane.

12 The $RETRACT$ variable is not included in the twin-engine equation as all of the twin-engine aircraft included in this study had retractable landing gear.
They assign a zero price to the nonsurvivors, and estimate the probability of survival \( f_t \) using the retirement distributions developed by Winfrey (1935) and estimates of the mean asset lives reported in Bulletin F published by the U.S. Treasury (1942). The weighted average price may thus be defined as \( P^* = f_t P(s) + (1 - f_t)0 \), where \( P(s) \) is the average price of the survivors and \( (1 - f_t) \) is the probability of not surviving.\(^{16}\)

Following Hulten and Wykoff, we correct for retirement bias by employing a weighted average price of the survivors and nonsurvivors. We adopt an alternative procedure for computing the probability of survival, however, as none of the Winfrey distributions provided a satisfactory approximation to the actual survival rates of the planes in our sample.\(^{17}\) As an alternative, we obtained data on the actual survival rates for a subset of the planes in our data set, and then used these data to estimate survival rates for the entire sample. The survival rates for 59 of the most popular models of aircraft sold by Beech, Cessna, and Piper were computed as follows. First, for each model, data on the number of planes sold in a given year and the serial numbers of each of the planes were obtained from the 1991 edition of the Bluebook. This yielded an original sample of 194,070 aircraft. Next, the serial numbers for each of the planes still registered, totaling 124,140 aircraft, were obtained from the 1991 edition of the Aircraft Registration Master File Tape issued by the FAA. It was possible to determine the survival ratio (the percentage of planes sold in a given year still registered) for a given model of a given age by matching the serial numbers of the planes still registered to the serial numbers of the planes sold in a given year.\(^{18}\) This procedure yielded a sample of 831 observations, where each observation represents the percentage of planes of a given model and age still registered in 1991.

The survival ratio is assumed to be a function of the age of the plane and the maintenance costs per hour of engine use (\( MAINT \)). In addition, since twin-engine aircraft are flown a greater number of hours per year than single-engine aircraft, the survival rate for twin-engine aircraft (\( TWIN \)) is assumed to be lower. The natural log of the survival ratio was thus regressed on age, \( MAINT \), and \( TWIN \). The results are as follows:

\[
\ln(\text{ratio}) = -0.2322 - 0.0011 * \text{MAINT} \\
(11.71) \quad (1.59)
- 0.0528 * \text{TWIN} - 0.0109 * \text{AGE},
(2.49) \quad (12.15)
\]

\( R^2 = 0.173 \)

where the values in parentheses are t-statistics. The results indicate that the survival ratio declines with the age of the aircraft and the cost of maintenance, although the latter result is not statistically significant at normal confidence levels. In addition, twin-engine aircraft have a lower survival rate than single-engine aircraft. Equation (3) was used to estimate model- and age-specific survival ratios (since \( TWIN \) and \( MAINT \) vary across models), which were in turn used to estimate the weighted average price for all planes of a given cohort.\(^{19}\)

V. Model Specification

We employ a vintage price equation to estimate the rates of depreciation and deterioration, and to test for the constancy of the rates over time. The vintage price equation employed in this study is developed in two stages. First, the model is specified under the assumption that assets depreciate at a constant geometric rate. The model is then generalized to accommodate alternative forms of depreciation. Define \( P_{v,t} \) to be the price of a used asset of age \( v \) observed at time \( t \), \( V_t \) as the age of the asset in year \( t \), and \( D_t \) as a dummy variable equal to 1 if the observation occurred in year \( t \) and 0 otherwise, with \( T = \{ t = 1975, 1980, 1985, 1991 \} \). The vintage price equation may thus be written as

\[
\ln P_{v,t} = \alpha + \delta V_t + \sum_{j \in T} \theta_j D_j + \sum_{j \in T} \gamma_j D_j V_t + e_{v,t}
(9)
\]

where \( \ln \) is the natural log operator, \( D_j V_t \) is an interaction term constructed as the product of the vintage and time dummy variables, and \( e_{v,t} \) is a random disturbance term, assumed to be normally distributed with zero mean and constant variance \( \sigma^2 \).

The time dummy variables \( D_t \) are included in equation (9) to control for upward shifts in the age–price profiles over time resulting from inflation. The rate of depreciation is given by \( \delta \ln P_{v,t} / \delta V_t = \delta + \gamma D_j \). For a given time period the rate of depreciation is geometric, but inclusion of the

\(^{16}\) Hulten and Wykoff (1977) demonstrate that this approach is consistent with the theory of replacement investment and depreciation developed by Jorgenson (1974).

\(^{17}\) For example, using the BEA (1976) average service life for pleasure aircraft of 10 years, the L1 Winfrey distribution indicates that 27.6% of the aircraft 13.0 years of age (the average life of the planes in our sample) would still be in operation. The actual survival data for pleasure aircraft discussed below indicate a survival rate of approximately 72% for aircraft of 10 years, the L1 Winfrey distribution indicates that 27.6% of the planes of a given model and age still registered in 1991.

\(^{18}\) This procedure implicitly assumes that all planes registered in a given year are still in active use. In addition, planes manufactured in the United States but sold to users in other countries and not registered with the FAA would not be included. The inclusion of nonactive aircraft will overstate the survival ratio, whereas the exclusion of foreign-based planes will understate the ratio. The estimated rate of depreciation will not be biased by the errors in the estimation of the survival ratio if the errors are independent of age.

\(^{19}\) The estimated survival rates were employed instead of the actual survival rates for two reasons. First, survival data were not available for all of the models used to estimate the rates of deterioration and depreciation. Using the estimated survival rates assures that all models are treated in a uniform fashion. Second, it was not possible to obtain complete survival data for a majority of the 59 models; most of the models are missing data for one or more years.
The hedonic price equation may be written as attributes of the assets. The Box–Cox version of the vintage possible to determine the rate of deterioration by estimating Equation (9) may be modified in several different ways to relax the assumption that the rate of depreciation is geometric. Following Hall (1971) and Lee (1978), the continuous age variable may be replaced with a series of age dummy variables. Although this approach imposes no a priori restrictions on the pattern of depreciation, the large number of dummy variables required (32 age dummy variables, together with 160 age–time or age–maintenance interaction terms) would result in an intractably large model. Alternatively, Hulten and Wykoff (1981a,b) demonstrate that it is possible to accommodate a wide variety of depreciation patterns by employing a Box–Cox power transformation. Using this approach \( \ln P_{v,t} \) is replaced by \((P_{v,t} - 1)/\lambda \), where \( \lambda \) is a parameter to be estimated. This model accommodates linear (\( \lambda = 1 \)) as well as geometric (\( \lambda = 0 \)) age–price profiles.20 The estimated rate of depreciation for the Box–Cox version of the vintage price equation is given by \( (\partial P_{v,t}/\partial V_t)/(1/P_{v,t}) = (\delta + \gamma_t D)\hat{P}_{v,t} \), where \( \hat{P}_{v,t} \) is the estimated price evaluated at the means of the data.

It is not possible to distinguish between the effects of deterioration and obsolescence using equation (9), as the vintage price equation fails to control for changes in the attributes of the assets over time. Following Hall (1971) it is possible to determine the rate of deterioration by estimating a vintage hedonic price function that includes data on the attributes of the assets. The Box–Cox version of the vintage hedonic price equation may be written as

\[
(P_{v,t}^\lambda - 1)/\lambda = \alpha + \delta V_t + \sum_{j \in J} \theta_j D_j + \sum_{j \in J} \gamma_j D_j V_t + \sum_{i=1}^n \beta_i X_{i,v,t} + \varphi M_{i,t} V_t + \epsilon_{v,t}
\]

where \( X_{i,v,t} \) represents the level of the \( i \)th attribute for an asset of age \( v \) observed in year \( t \), and \( M_{i,t} \) is the cost of a unit of maintenance for an asset of age \( v \) in year \( t \). To the extent that the attribute variables \( (X_{i,v,t} \) and \( M_{i,t} \) capture the effects of obsolescence, the rate of deterioration is given by \( (\partial P_{v,t}/\partial V_t)/(1/P_{v,t}) = (\delta + \gamma_t D)\hat{P}_{v,t} \), where \( \hat{P}_{v,t} \) is the mean of the required maintenance cost per hour of use for an asset of age \( v \) in year \( t \). The rate of deterioration is a function of both time and the cost of maintenance. The hypothesis that the rate of deterioration is inversely related to the cost of a unit of maintenance implies \( \varphi < 0 \).

VI. Empirical Results

Maximum-likelihood estimates of the parameters of the Box–Cox versions of equations (9) and (10), obtained using the average weighted prices, are presented in table 2.21 The estimated coefficients of the attribute variables in the deterioration equation generally conform to a priori expectations. The coefficients for \( HP \), \( SPEED \), \( CEILING \), and \( CARRY \) are all positive and significant at the 10% level or better using a one-tailed test for both types of aircraft, whereas the coefficient of \( RETRACT \) is positive and significant at the 1% level for single-engine planes. Contrary to expectations, however, the coefficients for fuel are negative and significant for both types of aircraft, and the coefficients for \( PRESS \) are positive, but insignificant. The estimated coefficients for the time dummy variables \( D_j \) are positive and significant in all equations, indicating an upward shift in the estimated age–price profiles over time.

In the deterioration equation the percentage change in price given a one dollar increase in the cost of engine maintenance per hour of use is given by \( (\partial P_{v,t}/\partial M_{v,t})(1/P_{v,t}) = (\beta_{M} + \varphi V_t)\hat{P}_{v,t} \), where \( \beta_{M} \) is the estimated coefficient for \( MAINT \), and \( \hat{P}_{v,t} \) is the estimated price, evaluated at the means of the data for each time period. For single-engine planes the result is negative and significant at the 10% level or better during 1975–1991. A one dollar increase in the maintenance costs per hour of engine use (an average increase of 20.61%) would reduce single-engine prices by 3.08% during 1975–1991. The impact of maintenance costs per hour on the prices of twin-engine planes is insignificant. The effect of a change in maintenance costs per hour of use on the rate of deterioration is determined by the coefficient of the maintenance–age interaction term.22 The coefficients of this variable are both negative and significant at the 1% level, a result consistent with Parks’ hypothesis that an increase in the cost of maintenance would lead asset owners to reduce maintenance expenditures, resulting in an increase in the rate of deterioration. Evaluated at the means of the data in 1985, a 10% increase in the cost of maintenance per hour of engine use would increase the rate of deterioration for single-engine and twin-engine planes by 1.04% and 1.08%, respectively.

The null hypothesis that the rate of deterioration or depreciation is constant over time implies \( \gamma_t = 0 \). This

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20 Hulten and Wykoff (1981a,b) and Hulten et al. (1989) estimate age–price profiles in which both the price and age variables have been transformed using the Box–Cox transformation. Transformation of the age variable in equation (10) requires that the Box–Cox parameter be greater than zero, as the age–time dummy variable interaction terms are not strictly positive. Attempts to estimate equation (2) with a transformed age variable proved unsuccessful, as the maximum-likelihood estimation procedure failed to converge.

21 The estimated parameters obtained using the average prices of the survivors are similar to the parameter estimates based on the average weighted prices. A copy of these estimates is available from the authors on request, as is a copy of the parameter estimates for the firm dummy variables.

22 The coefficient of the maintenance–age interaction term may also be interpreted as \( \beta_{M}/\partial M_{v,t} \). The negative sign on this coefficient implies that the reduction in price resulting from change in the cost of maintenance is greater for older planes than for newer planes. This interpretation also implies steeper age–price profiles for aircraft with high maintenance costs, and is thus consistent with Parks’ hypothesis.
rate of deterioration or depreciation is constant over the period of 1980–1991 implies $\gamma_{80} = \gamma_{85} = \gamma_{91}$. The chi-squared test statistics for the single-engine equation are 5.16 and 14.39 for the deterioration and depreciation equations, respectively. The corresponding values for the twin-engine equation are 40.48 and 14.15. The critical value at the 5% level is 5.99, implying that the hypothesis may be rejected for all but the single-engine deterioration equation. Finally, the estimated coefficients for the age–time dummy variable interaction terms for the years 1980, 1985, and 1991 are all positive and statistically significant at the 5% level or better. This result is consistent with the hypothesis that the rates of deterioration and depreciation declined following the rapid increase in the prices of new and used planes after 1975.

Estimates of the rates of deterioration and depreciation are presented in table 3. The average rate of deterioration for single-engine aircraft declined from 8.94% during 1971–1975 to 7.22% during 1980–1991, a decrease of 19.24%. The average rate of deterioration for twin-engine aircraft declined from 9.51% during 1971–1975 to 7.95% during 1980–1991, a decrease of 16.40%. Throughout 1971–1975 the average rates of depreciation for single- and twin-engine aircraft were 7.74% and 11.64%, respectively; the corresponding rates for the period of 1980–1991 are 6.33% and 9.04%. Between 1971–1975 and 1980–1991 the average rates of depreciation for single- and twin-engine aircraft thus declined by 18.22% and 22.34%, respectively. The decrease in the estimated rates of deterioration and depreciation after 1975 coincides with the sharp increase in new- and used-plane prices that occurred throughout the late 1970s and 1980s. These findings are consistent with the hypothesis that increases in the prices of new and used assets would lead owners to increase maintenance efforts, resulting in a decrease in the rate of deterioration or depreciation.

The estimated values of the Box–Cox transformation parameter $\lambda$ are negative and statistically significant at the 5% level or better in every case, indicating that the estimated rates of deterioration and depreciation are not geometric. Following Hulten and Wykoff (1981b), we test the ability of the geometric model to approximate the Box–Cox model by hypothesis was tested using a Wald test. The resulting test statistic is distributed as chi-squared with four degrees of freedom. The test statistics for the single-engine model are 122.41 and 30.43 for the deterioration and depreciation equations, respectively. The corresponding values for the twin-engine equation are 89.99 and 45.76. The critical value at the 1% level is 13.28, implying that the null hypothesis may be rejected in every case. The null hypothesis that the
replacing the Box–Cox transformed prices with the natural logarithm of the fitted values from the Box–Cox model in each of the regressions. The adjusted $R^2$ values for each of the four models exceeded 0.998, supporting their (p. 387) conclusion that “a constant rate of depreciation can serve as a reasonable statistical approximation to the underlying Box–Cox rates even though the latter are not geometric” at a given point in time.

The estimated rates of deterioration and depreciation obtained using the average weighted prices exceed those obtained using the average prices of the survivors. Throughout the period of 1971–1991 the average rates of deterioration for single- and twin-engine aircraft based on the average weighted prices were 7.91% and 8.57%, respectively. The corresponding averages obtained using the average prices of the survivors were 5.95% and 7.13%. The average rates of depreciation for single- and twin-engine aircraft based on average weighted prices during 1971–1991 were 6.89% and 10.08%, respectively. The corresponding averages obtained using the average prices of the survivors were 5.83% and 8.94%.

Changes in the rate of depreciation imply changes in the slopes of the age-price profiles. To illustrate this effect, profiles representing the relationship between the age of a plane and the price of a plane of age $t$ relative to the price of a one-year-old plane are presented in figure 1. The profiles are obtained by evaluating the estimated vintage hedonic price equations at the means of the data for each subperiod. The single-engine profiles for 1971 and 1975 are virtually identical, so only the 1971 profile is presented. The profiles for single-engine planes shown in figure 1A indicate a decrease in the rate of depreciation between 1971–1975 and 1980, and then a gradual increase in the rate of depreciation over the period of 1985–1991. The twin-engine profiles for 1971–1975 and 1980–1985 are virtually identical, so only the 1971 and 1985 profiles are shown. The profiles for twin-engine planes shown in figure 1B indicate a continual decrease in the rate of depreciation over the entire 1971–1991 period. The changes in the slopes of the estimated age-price profiles are consistent with the estimated rates of depreciation reported in table 3.

VII. Conclusions

The assumption that assets depreciate at a geometric rate that is constant over time implies that the rate of depreciation may be treated as an exogenous variable, independent of economic forces. An exogenous rate of depreciation is inconsistent with much of the theoretical work on replacement investment and optimal asset durability that maintains that the rate of deterioration should be a function of interest rates, taxes, the cost of maintenance, and the prices of new and used assets. This study has tested two of the hypotheses that emerge from the literature on optimal asset durability: (1) increases in the price of new or used assets should lead owners to delay replacement and increase maintenance, thus reducing the rate of deterioration, and (2) increases in the cost of maintenance should lead owners to reduce maintenance efforts, thus increasing the rate of deterioration.

These hypotheses were tested using a vintage price equation to estimate the rates of deterioration and depreciation. The estimated model is sufficiently flexible to accommodate linear and geometric, as well as other age-price profiles. The model was estimated using data on the retirement-adjusted prices and characteristics of used single- and twin-engine aircraft sold in the United States over the period of 1971–1991. The rapid increase in the prices of new and used planes after 1975, resulting from an increase in liability expenses, makes it possible to test for the effects of increased prices for new and used assets on the rates of deterioration and depreciation. In addition, the availability of required maintenance cost data allows for a test of the impact of maintenance costs on the rate of deterioration.

The empirical results indicate that the annual average rate of depreciation for single- and twin-engine planes declined between 1971–1975 and 1980–1991 by 18.22% and 22.34%, respectively, a result that is consistent with the hypothesis that increases in the prices of new and used assets reduce the rate of depreciation. The estimated rates of deterioration for single- and twin-engine aircraft declined between these two periods by 19.24% and 16.40%, respectively. In addition, required maintenance costs were found to be positively and significantly related to the estimated rate of deterioration. A 10% increase in maintenance costs per hour of use would reduce the rate of deterioration for single- and twin-engine aircraft by 1.04% and 1.08%, respectively.

The results of this study are not meant to imply that government agencies should be expected to adopt age- and asset-specific rates of depreciation in computing capital stocks or the service price of capital. Such a conclusion
would be clearly unwarranted on the basis of a single study, and infeasible in terms of the information required. The results of this study do, however, call into question the frequently invoked assumption that assets depreciate at a geometric rate that is stable over time. It is our hope that these results will help to motivate the development of more realistic models of asset durability in which the rate of depreciation is treated as an endogenous variable.

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