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ORIGINAL ARTICLE

Banknote Life in India: A Survival Analysis Approach

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Abstract

India's currency-to-GDP ratio indicates a strong and persistent demand for cash. Despite the withdrawal of two high-value banknotes in 2016 and the recent economic contraction due to the COVID-19 pandemic, cash continues to rule in India. Although there is extensive work on the demand for cash in India, relatively little is known about the quality and supply of banknotes. This paper provides an overview of currency management policies in India using publicly available annual aggregate issuances and disposals data from the Reserve Bank of India (RBI). We model the life of a banknote using survival analysis models, finding that low-value banknotes (INR 10 and 20) have a median life of 4–5 years. The estimates of longevity of a banknote are significantly associated with velocity of circulation as well as exogenous shocks. We demonstrate the value of survival analysis methods in informing currency management policies in India and providing avenues for future work in this domain.

Keywords Banknotes · Banknote life · Hazard rates · Currency management · Central banks

JEL Classification C41 · E42 · E58

Introduction

Paper currency remains a critical aspect of the Indian economy despite years of high economic growth, rise in the availability of digital payment methods, as well as recent policy measures aimed at curbing cash use. For example, in December 2016, the Reserve Bank of India (RBI) announced the withdrawal of two high-value

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banknotes (₹500 and ₹1000) overnight, aimed at curbing illegal activities (such as terror financing) and transitioning India to a less-cash economy. In 2016, the key measure of the demand for cash, the currency-to-GDP (C-GDP) ratio declined to nearly 8%, but has since returned to pre-demonetization levels and stands at nearly 14.5% as of 2021 (ET Now Digital 2021). This suggests that demand for cash (or paper currency) persists, and thus the RBI's currency management function becomes more critical for sustained economic productivity and growth in India. It is important to note that there was a decline in cash-based transactions between 2013 and 2016 with the introduction of the Unified Payments Interface (UPI) as well as a strong policy push for cashless transactions. There has been further evidence on the persistence of cash demand post-demonetization in India (Chodorow-Reich et al. 2020; Karmakar & Narayanan 2020; Reserve Bank of India 2019) as well. Thus, given the upheaval in cash demand and increased supply that India has seen in recent years, it becomes important to understand how currency management policies are framed, specifically those pertaining to printing and supply of paper banknotes.

Considering the role of cash in day-to-day commerce, and as Karmakar and Narayanan (2020) point out, if there are substantial lags between currency demanded and currency supplied, the resulting liquidity issues may lead to welfare losses incurred by households. As Loizidou et al. (2022) show, analysing cash life cycles is critical for both banknote issuers as well as companies that print banknotes. Any mismatch in the issuance and demand for banknotes arising out of currency management functions could result in a shortage of notes when cash demand is high (e.g., seasonal fluctuations as Cabrero et al. 2009 suggest). It could also result in a surplus of notes and additional liquidity when there is lack of cash demand. Moreover, this mismatch could also result in erosion of trust in the banking system, leading to loss of consumer confidence (Mazzotta et al. 2014). Similarly, Tagat et al. (2020) indicate that there are behavioural factors influencing cash usage and holdings that point toward a more deep-seated preference for cash over alternate payment mechanisms, driven both by risk preferences and favourable attitudes towards cash usage.

In this context, if cash demand imbalances persist, managing supply efficiently and framing appropriate currency management policies begin to assume critical importance. This is particularly the case in a country like India, where the cash-to-GDP ratio remains well above 14% even after policy experiments aimed at reducing reliance on cash, as well as a recent spike in the volume of online transactions due to COVID-19 pandemic-related restrictions. In terms of supply and management of currency, one needs to examine not just the availability of cash at ATMs and the supply chain of paper banknotes, but also the quality and features of the banknotes supplied (Massoud 2005).

In this paper, we aim to examine the issuance, disposal, and life of banknotes in India. In order to fully understand how and why banknotes are disposed, we frame these in the context of the banknote fitness rules of the RBI (Reserve Bank of India 2010). Our main empirical contribution is in the form denomination-wise estimates of the stock and mean lifespan of banknotes across different series over time using net issuance and disposals data from the RBI between 2003 and 2016. Methodologically we draw on recent innovative applications of duration models and simulation in the domain of currency management (Aves 2019; Rojas et al. 2020; Rush 2015) and contrast these results with other prevailing methods.

The remainder of the paper is organized as follows. Sect. "Currency management in India" provides an overview of currency management policies in India, outlining the cycle of production, issuance, circulation, and disposal, as well as the cost of producing banknotes. Sect. "Methodology" lays out the empirical methodology using aggregate data on issuances and disposal of banknotes from the RBI. It also provides a process overview of the application of survival models in the context of banknote lifecycles. Sect. "Results" contains the results and key findings of the steady-state and survival analysis estimates of the life of a banknote. Sect. "Concluding Remarks and Implications for Policy" concludes with implications for currency management in India and provides avenues for future work.

Currency Management in India

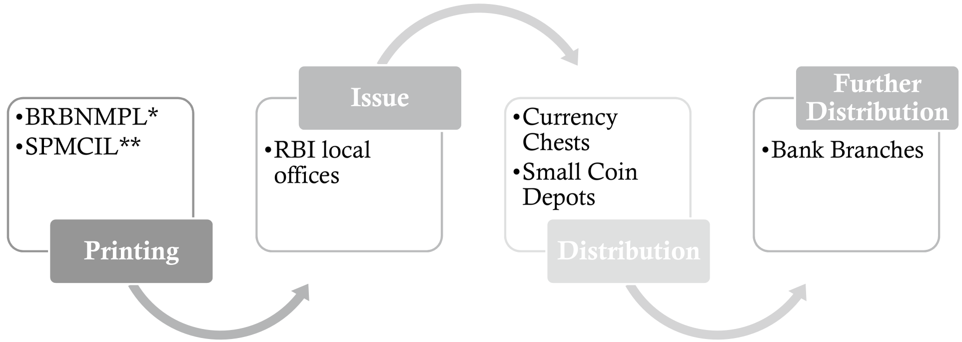
In this section, we provide a broad overview and background to currency management functions of the RBI in India. These are related to three areas: (a) Printing and note issuance; (b) Note disposals and inventory management, including paper banknote fitness criteria; and (c) the cost of printing notes. On each of these, we provide publicly available data from the RBI.

Printing and Issuance

As in many other jurisdictions, there are two aspects (broadly) to currency supply in India: printing and issuance. These are managed through printing presses, mints, issue offices, currency chests, and small coin depots at various locations. Typically, a commercial bank (such as the largest state-owned bank, the State Bank of India) will double up as a currency chest in order to organize logistics of banknote distribution. Figure 1 provides a summary of the banknote distribution network in India managed by the RBI.

Printing of paper banknotes in India[1] are via subsidiary companies of the RBI and the Union Government of India, the Bhartiya Reserve Bank Note Mudran Private Limited (BRBNMPL 2020) and the Security Printing and Minting Corporation of India Limited (SPMCIL). BRBNMPL operates two printing presses in India, both set up in 1996, one in Mysore (Karnataka) and another in Salboni (West Bengal). BRBNMPL has the capacity for both printing presses stands at 16 billion paper banknotes a year, which is well above the average of 0.25 million banknotes on average that have been supplied and issued since 2018–19 (Reserve Bank of India 2021). Subbarao (2010) provides a useful overview and history of the currency management in India.

[1] Paper banknotes in pre-independent India were printed in London by De La Rue, and it was only in 1928 that a printing press of Nashik was established to print paper currency notes. Older printing presses (the status of which are currently unknown) were set up in Dewas in Madhya Pradesh in 1975 (BRBNMPL 2020).



* Bhartiya Reserve Bank Note Mudran Private Limited

** Security Printing and Minting Corporation of India Limited

Fig. 1 Network of banknote distribution in India

Once the banknotes are printed, they are distributed to bank branches by the RBI's local offices and various currency chests spread across India. In short, currency chests are storehouses for holding paper banknotes and coins on behalf of the RBI at various locations in India. As of the end of 2019, there are 3812 currency chests[2] in 31 cities that supply paper banknotes and 3519 small coin depots in charge of coinage. Notably, the number of currency chests has actually declined over time, from 4422 in 2002 to 4247 in 2010, and 4075 just prior to demonetization in 2016. As of 2020, the RBI is considering redesigning the model through which banknotes are distributed, where larger currency chests redistribute paper banknotes to smaller currency chests in a specific geographical location (Reserve Bank of India 2020a).

Inventory Management and Disposal Rules

In terms of inventory management, most Central Banks globally follow a fixed destruction rate criterion (Massoud 2005). This means that in most Central Banks, there is a constant proportion of banknotes that are expected to be disposed annually. Post-issuance, it is therefore important for Central Banks to decide what is a 'fit' banknote. In India, The Clean Note Policy of 1999 (Reserve Bank of India 1999) laid down the rules for note fitness and return in case of damage due to ink-wear, soiling, mutilation, or other wear and tear. More recently, the Fitness Rules of 2010 provided an updated set of regulations for determining paper currency fitness at banks (Reserve Bank of India 2010). Primarily set to ensure that notes are able to be sorted mechanically at banks, a fit banknote must satisfy all of a set of fitness parameters (including acceptance by sorting machines, visual or physical defects, and mutilation or other imperfections), failing which it is considered for disposal or destruction by the RBI.[3] Further, a note is unfit if "*is not suitable for recycling because of its physical condition or belongs to a series that has been phased out by Reserve Bank of India* (Reserve Bank of India 2010)."

Cost of Printing Banknotes

In determining cash management policies, central banks also take into account the cost of production and distribution related to banknotes (Van Hove 2015) including the costs and returns on investment in printing technology and materials. For example, Wakefield et al. (2019) use a cost-benefits framework to assess the economic rationale for shifting to longer-lasting polymer-based banknotes in Australia. They find a net cost saving of nearly 1 billion AUD (approx 750 m USD) over a period of 25 years since the introduction of more expensive to produce polymer banknotes

[2] In order for a commercial bank to set up a currency chest, it must be able to provide adequate space for a vault and have a processing capacity of 0.6 million paper banknotes a day, with a limit of storing INR 10 billion.

[3] It is worth noting that fitness sorting parameters by machines may be very different than what end-users (humans) might perceive to be a fit banknote. These are indeed likely to be subjective and not typically follow a specific pattern and are therefore harder to gauge when deciding the actual proportion of 'acceptable' banknotes in circulation (Deinhammer and Ladi 2017).

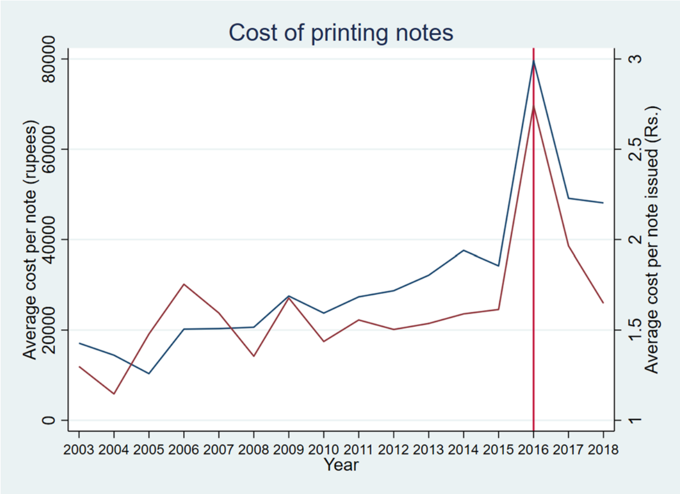


Fig. 2 Cost of banknote printing in India. Red line represents the per note issuance cost in INR, whereas the blue line represents the average issuance cost in INR

due to reduced wear and tear in use. Similarly, there has been research in the US that uses a combination of approaches to examine the cost of production of banknotes (Bouhdaoui et al. 2013), which constitute processing (monitoring the quality of banknotes produced by varying the ink or material used) and replacement (replacing unusable or torn banknotes, which are contingent on the lifespan of a typical banknote). Much of the benefits are in the form of seignorage, which is the difference between the face value of the currency and its cost of production, which can vary by denomination.

In India, data on the cost of printing banknotes is not available per denomination and thus it is not possible to directly assess if there are substantial differences in production of larger or smaller-value banknotes on a per unit basis across differing designs or production returns to scale. However, the RBI provides the cost of security printing as part of its Income Statement in the Annual Report (Reserve Bank of India 2020b). Figure 2 plots the total cost of printing banknotes as well as the average cost per note over time since 2003. Unsurprisingly, the cost almost doubled in lead up to the period of demonetization (2016), driven by the printing and issue of two new series of banknotes (INR500 and INR2000) to replace all prior series of the same denomination in circulation. Notably, since demonetization, alongside usual production of new series of paper currency, a new denomination (INR200) has been issued, potentially leading to an increase in the cost of printing banknotes. The average cost per note printed follows a similar pattern, increasing from INR 1.5 pre-2016 to INR 2.7 during demonetization, and resettling back to pre-demonetization levels as of 2019. This suggests that the marginal costs of printing currency in India may not always decrease with increased supply especially where the production of the supply is temporally restricted.[4] It may therefore be more cost effective to have steady replacement of currency notes over time.

The major components of printing costs in India include the costs of producing ink, procuring paper, and printing and the supply of these components are largely vertically integrated into production. As mentioned previously, the printer BRBNMPL owns and runs a paper mill and produces ink to meet banknote production requirements. Recent reports of the RBI also document innovations in developing indigenous inks and printing capacities (Reserve Bank of India 2019) as well as setting up an automated cash management system (Reserve Bank of India 2021).

Issuance and Disposal of Banknotes

In this subsection, we outline data on the issuance and disposal of banknotes for the period between 2003 and 2018. In line with the fitness and disposal policies of the RBI, once a banknote does not meet fitness criteria outlined previously it is returned to the RBI for disposal. Figure 3 shows the issue and disposal, respectively, of small-value banknotes by the RBI since 2003. The findings in this figure are somewhat consistent with the idea that lower-value banknotes are most likely to be used for fulfilling transactions in cash and are rarely used as store of value (Rogoff 1998; Drehmann et al. 2002) and are therefore likely to witness greater velocity of circulation. Thus, the trends in issuance and disposal could also reflect that the nature of use of these notes might be increasing, potentially due to more economic activity. However, in 2016 there was a substantial drop in the issue of these banknotes as well as a reduction in bank handling of smaller-value banknotes that were considered unfit and returned to the system. This could be on account of RBI's focus on withdrawing the demonetized banknotes and remonetizing the economy with the newer issues. We discuss this when dealing with large-value banknotes.

Figure 4 shows the issuances and disposals for INR100 notes between 2003 and 2019. Similar to the smaller value banknotes, markedly fewer INR100 notes were issued and disposed of during demonetization.

Finally, Fig. 5 shows the variation in issue and disposal of large-value banknotes in India since 2003. This data is only available for the older series of the INR500 banknote (pre-2016) and the (now withdrawn) INR1000 note. Overall, there appears to be an upward trend in the issuance and disposal of high-value banknotes, which constituted more than 70% of the currency in circulation post-2005. There is also evidence of some substitution in the issue of notes—for example, in 2011, the RBI issued more INR1000 notes and many fewer INR500 notes. However, no similar trend is observed in 2014, when there was a large spike in the issue of INR500 notes, indicating that these could be measures intended to diversify the velocity of circulation to other denominations. Specific currency management policies may be

[4] It is also possible that input costs may have risen (although no breakdown of components related to such printing costs are available), since the RBI would demand much of the available supply of specialized ink and paper, potentially driving their prices up. This is of course notwithstanding the steady increase of reliance on local technology and machinery.

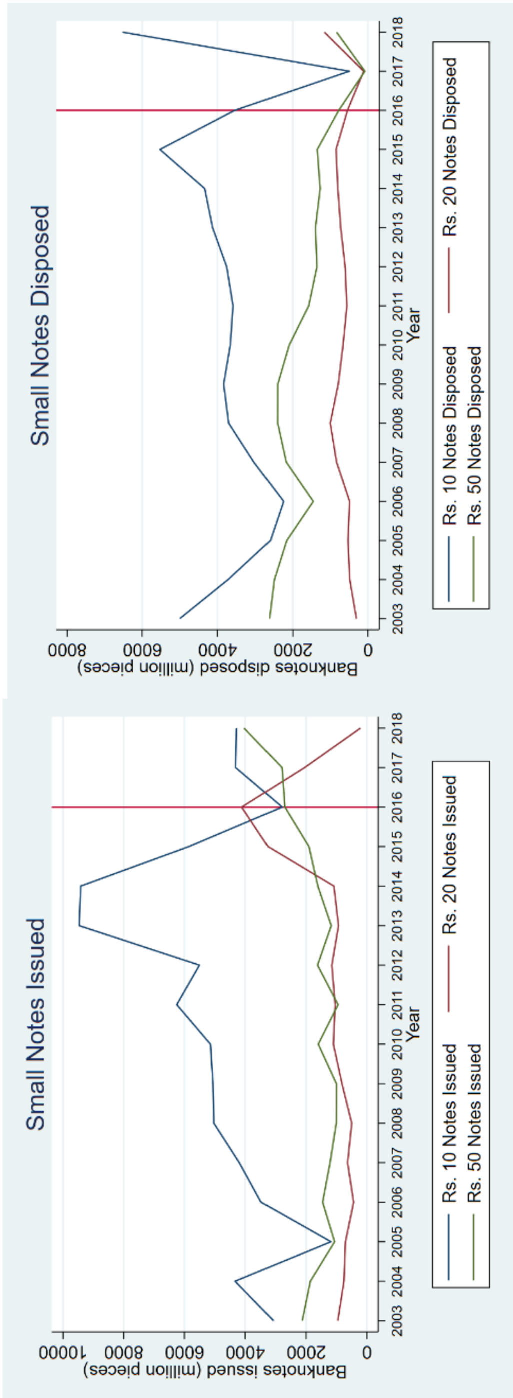


Fig. 3 Issuances and disposal of small-value banknotes (INR10, 20, and 50)

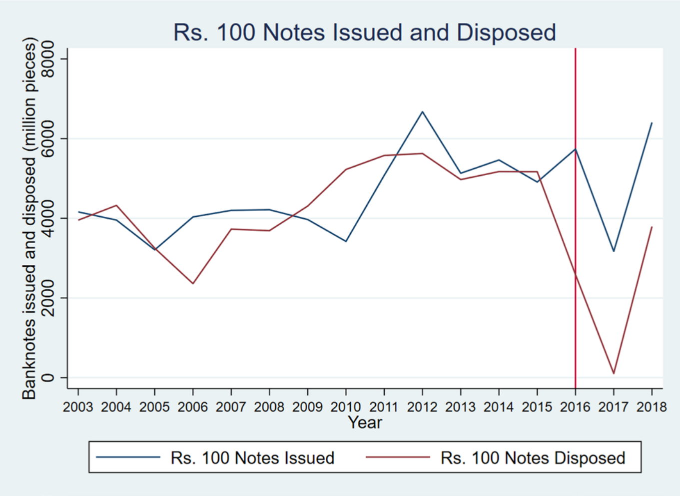


Fig. 4 Issues and disposal of INR100 banknotes

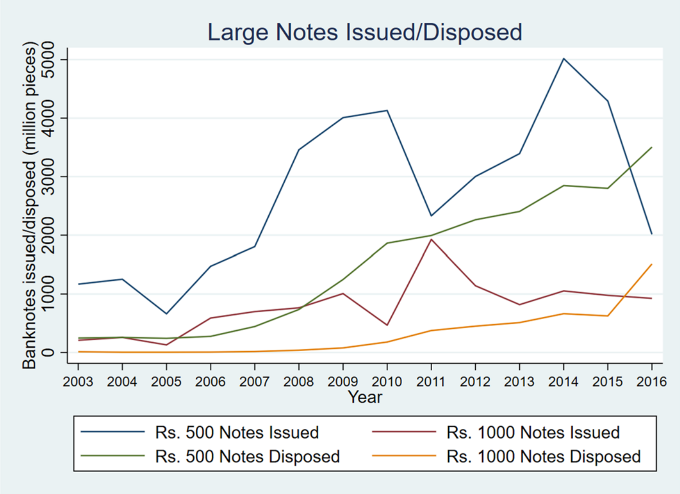


Fig. 5 Issues and disposal of large-value banknotes (INR500 and 1000)

underlying these issue patterns, and there is work on ideal denomination structure (Bajaj & Damodaran 2020; Waknis 2019) for India and other countries (Bouhdaoui & Van Hove 2017) that can be considered in line with the recent introduction of new medium-value banknotes (e.g., INR 200).[5]

[5] For more on the denomination-wise share in velocity of circulation patterns, we refer the reader to Fig. 11 in the appendix. This shows that the INR 10 banknote makes up for most of the velocity, which declined after demonetization in 2016.

Some banknotes may be removed from active circulation to be held as a store of value and ultimately some of these may be permanently lost or be replaced as legal tender by subsequent series without being returned for disposal. In line with the seasonality of currency demand in India (Bhattacharya and Joshi 2001; Raj et al. 2020), it is also likely that fluctuations in banknote circulation are concentrated in specific times of year. Once these demands are met, banknotes are assumed to return to the banking system and are once again examined for fitness before recycling them in the economy. Particularly for large-value banknotes prior to demonetization, the destruction rate in India has been increasing. Unlike certain other economies, there was no significant shift in the quality of banknotes (apart from changes in ink used) issued for India. This is similar to the EU and the US, which predominantly uses cotton-based paper currency. In contrast, economies such as Australia, Canada and the UK, which have switched to polymer-based currency notes. The RBI has discussed field trials of plastic or varnished banknotes in their annual reports since 2015, but no public information is available on their implementation or current status. Thus, our analysis of the life of a banknote in the Indian context is motivated by the issuance and disposal rates laid out in Figs. 3, 4, 5 and assumes that paper banknotes disposed are largely on account of inkwear (discolouration, soiling or similar) or mechanical defects (staples, tears, mutilation).

Methodology

In this section, we outline two methods of assessing the life of banknotes following Rush (2015): the 'traditional' steady-state or turnover method, and the Feige (1989) steady-state method, as well as recent innovations applying survival analysis methods. The traditional/steady-state methods are tools that central bankers and suppliers of currency may use to estimate roughly the duration of banknote circulation. Survival analysis methods are more statistically rigorous, in that the probability of a banknote returning for disposal is predicted as a survival function driven by macromonetary factors (Aves 2019; Rush 2015).

Steady-State Methods

As the name suggests, the traditional steady-state or turnover method (Rush 2015) simply tracks the stock of banknotes on issue (averaged over a 12-month period) relative to the total number of banknotes destroyed (in the same 12-month period). This would translate to the ratio of issued to disposed from the data presented in Figs. 3, 4, 5. This is essentially a measure of turnover rate that computes the average number of years that an issued banknote is circulated until it returns for disposal (likely on account of being deemed unfit as per the fitness rules discussed in earlier sections).

As Rush (2015) states, a key limitation of the traditional steady-state methodology is that the measure varies widely when there are disproportionate issues relative to disposals of a banknote in a given period. As a partial solution, Feige's (1989) 'banknote life' is an alternate measure that makes a distinction about the number of times a banknote is used in a transaction over its assumed lifetime of 12 months. This is a key assumption made by this method which drives the estimation of the life of a banknote. Thus, the Feige method for banknote life (for the D^{th} denomination) uses the formula:

$$F_D = \frac{Meanstockofbanknotesonissueover12months}{(Annualdisposal + Annualissuances)/2}. \quad (1)$$

This is a marginal improvement over the traditional-steady-state method as it does not assume a constant hazard or destruction rate.

One of the key limitations of these methods is that they assume that the probability of a banknote being deemed unfit is assumed to be independent of their age (i.e., the year that they were issued). They are also typically unable to take into account changes in currency management, such as changes in quality of banknote production or other innovations in their supply. One of the key changes that the RBI does regularly undertake in this regard is new issuances with newer security features and new inks. Furthermore, as Rush (2015) states, these methods do not account for exogenous changes in demand for currency, such as the global financial crisis (Cusbert and Rohling 2013) or similar macroeconomic events. In India, there might also be changes in the network of issuance and disposal of banknotes (such as the Cash Distribution and Exchange Scheme, or CDES) that may affect banknote life as measured by these methods.

Survival Analysis

Survival models are gaining traction in the literature on currency management and life of banknotes (Aves 2019; Deinhammer and Ladi 2017; Rojas et al. 2020; Rush 2015). In order to further examine life of banknotes across various denominations, recent studies (Rush 2015; Aves 2019) have made use of survival models that are common in the medical literature in tandem with statistical optimization algorithms to fit and model survival curves across different series of a currency denomination over time. Although more commonly used in the biological sciences, survival analysis is useful in explaining the 'death' of a banknote as one that is removed from circulation after a particular point in time. Unlike a typical application, however, central banks do not maintain data on each banknote in circulation once it is disposed, and data available is more aggregate in nature.[6] Further, by using such survival models, we are able to relax the assumption of the constant hazard rate and use standard probability distributions to estimate models of the survival function for banknotes. The actual number of fit banknotes is defined in these models as the total banknotes ever issued less the total number of destructions up to that point in time. Each issuance (for each denomination) therefore will be characterized by a potentially unique

[6] The Bank of Canada and the Bank of England are both beginning to monitor banknotes using serial number tracking features, with their advanced banknote processing technologies (Rojas et al. 2020). At the time of writing, there is no clear indication if the RBI has similar capacities or programs.

survival function—a likelihood that defines the fraction of fit banknotes based on a set of parameters)—and can be used to compute the expected number of aggregate fit banknotes.

We therefore follow Rush (2015) and Aves (2019) in proposing a joint survival function using aggregate issuances and disposals data from the RBI. Thus, the total quantity of surviving banknotes at any given date and denomination is a sum of all surviving banknotes from each issuance. This is a tenable description since at the time of every issuance, individual banknote pieces are identical and do not differ in quality or other characteristics. In the sections that follow, we describe our survival and death functions, and the destruction and hazard rates.

The Model

For a time of destruction T, the survival function is defined as $S(t) = P(T > t)$, where the function $P(T)$ describes the probability that a banknote will survive (not be disposed) at time period T. The lifetime distribution function (which is a cumulative density function for the probability that a banknote will be destroyed at time t) is given by $L(t) = P(T \leq t) = 1 - S(t)$. Scaling the first derivative of the lifetime distribution function ($\dot{L}(t)$, which is the destruction rate) by the proportion of surviving banknotes yields the hazard rate (Aves 2019), given by: $\dot{L}(t)/S(t)$. This quantity is essentially the instantaneous failure rate at a given time, and may also be interpreted as the negation of the logarithmic derivative of the survival function S(t). For instance, if S(t) corresponds to an exponential distribution, which is the canonical distribution for a survival function, then the hazard rate is constant, reflecting the memoryless nature of the distribution. For other distributions the magnitude of this quantity may indicate other properties of the distribution, such as a higher rate of failure for older individuals (a tendency to wear out over time), or the opposite phenomenon (a tendency towards early failure rather than later).

As Rush (2015) notes, the expected number of 'fit' banknotes at any given time can be defined as the sum of new issuances since banknote production commenced (in this case, since data on banknote production is available from the RBI), multiplied by the issuances' survival function. Based on aggregate data, this is given by

$$E\left(F_t|\boldsymbol{\alpha}\right) = \sum_{n=1}^{t} S\left(t_n, \boldsymbol{\alpha}\right).I_n, \tag{2}$$

where F_t is a measure of outstanding banknotes which is derived from aggregate RBI currency management data as the sum of total issuances less the disposals for that particular denomination (over the total number of time periods, t) and I_n is the number of issued banknotes at time n. $\boldsymbol{\alpha}$ is a vector of parameters that governs the shape of the survival function S. As described elsewhere, this vector is likely to factor in determinants of banknote survival that cannot be fully captured in the data (e.g., changes in handling of banknotes, preferences for cash payments, among others). In our survival model, the functional form of the survival function determines what is contained within $\boldsymbol{\alpha}$. We also define an issuance function in this manner for each banknote denomination (INR 10, 20, 50, 100, 500, and 1000). The key addition that we are able to make to the literature on currency management in using this approach relates to the use of non-linear regression analyses with this survival function applied to the case of India. Thus, in contrast to the steady-state approaches, we are able to explain or predict the probability of banknote disposal (and fitness) using currency management policies. A notable shortcoming remains, as Rush (2015) acknowledges, which is that there is very little in terms of demand-side preferences or tastes that one can account for in this analysis (e.g., preferences for cash). Finally, our non-linear regression specification that estimates the joint survival function is defined as

$$t_n = e^{X_n{'}\beta} + t_{n-1}. \tag{3}$$

In line with Aves (2019), time is defined as 'activity time'[7] (i.e., the duration for which banknotes are assumed to undergo wear and tear as a result of circulation in the economy). Thus, t represents activity time, and $\boldsymbol{X}$ is a vector of explanatory variables (dummy variables for changes in banknote series, global financial crisis, demonetization, and the velocity of cash circulation), and β is the set of parameters to be estimated.

In general, in work that uses survival analysis, either the Weibull or the generalized Gamma distribution are preferred due to their flexibility in approximating other distributional forms. These distributions are determined by two or three parameters, which determine the scale, shape and location of the function. For a detailed discussion on the choice of probability function (i.e., the functional form), we refer the reader to Rush (2015) and Aves (2019). Since there are no prior studies that suggest appropriate values for these parameters, a key challenge is in calibrating the parameter values so that the model converges. There is little to no statistical guidance on what appropriate values are as these could differ by the nature of the data as well as the number of explanatory variables and observations under consideration.

Selecting Explanatory Variables

Literature on currency management is small and sporadic and is largely restricted to countries where central banks maintain monthly data on currency notes issued and destroyed. In the case of India, the RBI makes available only annual data on currency issuances and disposals (by denomination), and data on banknote quality changes or changes in issuance processes is scarce outside the annual reports. To help explain the probability of survival (and disposal) of a banknote within a denomination class, we start with indicator variables that prior work suggests will play a role in the life of banknotes. First, we create two indicator variables for macroeconomic conditions that have been shown to influence the circulation and velocity of currency used in transactions: the global financial crisis (GFC, henceforth), and the demonetization

[7] Note that this necessitates an assumption on the currency notes that falling out of circulation or being lost is not subsumed in the category of notes being unfit and therefore being returned for disposal. It also means that we are unable to take such banknotes into account in the analysis. Unfortunately, there is no data published by the RBI on how many banknotes precisely are deemed as missing or lost, hence we are unable to substantiate this assumption further.

and remonetisation period spanning December 2016 to April 2017. The GFC variable for India takes a value of 1 for the period between August 2008 and December 2010 (Dua and Tuteja 2016). Similarly, the demonetization variable takes a value of 1 for the period between December 2016 and April 2017, and zero otherwise.[8]

Furthermore, our model considers the process by which the circulation of notes change—i.e., the velocity of transactions using cash that could increase the frequency of usage thus shortening the time to becoming ‘unfit’. To proxy for this, we use the ratio of ATM withdrawals to currency in circulation (Aves 2019). This also helps us overcome the shortcomings of the steady-state models presented previously, since we are able to account for the role of mechanical defects and inkwear in the life of a banknote. Thus, we can do away with the assumption implicit in turnover models that a banknote is assumed to remain in circulation until it is returned to the RBI for disposal.

As such, Eq. (3) for the ‘activity time’ is estimated as

$$t_n = e^{\beta GFC_n + \beta CIC_n + \beta Velocity_n + \beta Velocity_n * t} + t_{n-1}, \tag{4}$$

where *GFC* is an indicator variable equal to one between October 2008 and August 2009 as well as between December 2016 to April 2017 that account for any precautionary demand for banknotes during the global financial crisis and the demonetization and remonetisation periods; *CIC* is the total currency in circulation by value; *Velocity* is the ratio of monthly ATM withdrawals, by value, to circulating banknotes, by denomination as a proxy for the velocity of cash; and *Velocity*t* is the Velocity variable times a time trend.

However, banknotes (especially of higher value) might be used as a store of value and hoarded for a long time until changes in the macroeconomy might induce changes in the composition of notes circulating.[9] To account for such variations in cash use by denomination, the choice of probability distribution is critical. Prior work in this domain has suggested the use of the Weibull (Rush 2015) and the generalized gamma distribution (Aves 2019). The generalized gamma (GG, henceforth) allows for a wide variety of possibilities in the behaviour of the survival function and is commonly used in various survival applications.

The Weibull distribution is the probability distribution admitting the density:

$$f(t) = \frac{k}{\lambda}\left(\frac{t}{\lambda}\right)^{\{(k-1)\}e^{\left\{-\left(\frac{t}{\lambda}\right)^{k}\right\}}}, \tag{5}$$

[8] Another candidate for explaining variations in cash life cycles could be related to the informal sector use of banknotes. Most informal market transactions were cash-based, especially in the pre-UPI era. Therefore, it is likely to have an independent impact on banknote life during the study period. However, we were unable to impute the annual data on self-employment as a measure of informality, and thus leave it as an exercise for a future paper. We are grateful to an anonymous referee for this suggestion.

[9] The trend in issuances and composition of notes in circulation has changed over time in India since 2002 (the starting period for this analysis). For example, there was a sharp increase in the issue of INR 10 banknotes between 2010 and 2014, but this has since reverted to pre-2010 levels. The demonetization and remonetization period also involved shifts in structure of currency issuances and disposals by RBI. We incorporate this by using dummy variables for changes in issuances during this period.

for $t \geq 0$, and $f(t) = 0$ for $t < 0$. Here k and λ are positive parameters, called the *shape* and *scale* parameters, respectively. Note that a random variable with a Weibull distribution is positive with probability 1. Our objective is to estimate $f(t)$ as a survival function with explanatory variables and estimate the probability of survival using the functional form specified in Rush (2015). We adapt the GG function from Aves (2019) to take a similar form.

The generalized gamma distribution is the probability distribution admitting the density:

$$f(t) = \Gamma\left(\frac{d}{p}\right)^{\{-1\}\left(\frac{p}{a^d}\right)\mathrm{t}^{\{(d-1)\}e^{\{-\left(\frac{t}{a}\right)^p\}}}}, \tag{6}$$

for $t \geq 0$, and $f(t) = 0$ for $t < 0$. Here *a, d,* and *p* are positive parameters which determine the properties of the distribution. Note that a random variable with a generalized gamma distribution is positive with probability 1, which is appropriate in light of our interpretation of t as time until failure. Appropriate choices for the parameters *a, d,* and *p* can yield simpler important distributions, such as, the exponential, Weibull, and gamma distributions, but the generalized gamma distribution is more flexible than these and as a result is popular in survival analysis (Cox et al. 2007; Aves 2019).

One noteworthy feature of the generalized gamma is that the failure rate, which is defined as $\Lambda(t) = \frac{f(t)}{1-F(t)}$ with *F(t)* the cumulative distribution function, takes a complicated form that allows for a variety of different behaviours of a banknote. In particular, the failure rate for a generalized gamma need not be monotone in t. This contrasts with the Weibull distribution, whose failure rate is assumed to be monotonically increasing.[10] In what follows, we discuss results of estimation from both models, acknowledging caveats associated with using annual data, which is lower frequency than monthly data typically used in modelling banknote life using survival analyses. For optimization, we use the non-linear least squares (NLS) function in R, which provides a set of summary statistics following iteration through model parameters. Using NLS poses some challenges and requires key assumptions for the model to converge, especially with a small number of observations. The optimization technique is sensitive to the initial values, the number of variables specified, and potentially any measurement error. We attempt to address these concerns by iterating the model using a limited number of explanatory variables, restricting optimization to non-negative values, setting assumptions on the initial values (see discussion above), and restricting our analysis to a denomination that has a median lifespan of 4–5 years.

[10] This assumption is necessary to reflect the idea that banknotes that undergo wear and tear during circulation and use cannot potentially "improve" their quality. For example, the practice of taping together torn or mutilated banknotes may actually attract attention to the fact that it is mutilated, and therefore increase the likelihood of return.

Table 1 Mean and median steady-state banknote life (2003–2016)

Denomination	Mean	Median	SD
INR10	4.92	5.31	2.48
INR20	5.69	4.99	4.01
INR50	2.94	2.50	1.87
INR100	3.77	3.06	1.92
INR500	7.90	5.73	4.43
INR1000	42.49	19.03	46.16

Table 2 Mean and median Feige steady-state banknote life (2003–2016)

Denomination	Mean	Median	SD
INR10	4.25	4.04	2.48
INR20	3.69	3.44	0.84
INR50	2.83	2.76	0.63
INR100	3.41	3.19	0.93
INR500	4.06	3.99	1.44
INR1000	5.10	4.59	2.78

Results

Traditional/Steady-State Results

Table 1 shows the average and median banknote life computed by denomination using the traditional steady-state method. Since data was manually scraped from currency management reports of the RBI, they are available annually between 2003 and 2020. Notably, we do not include estimates of the post-2016 data since there are considerable changes to the issuances and disposal during this period. The high standard deviations suggest that the measure is volatile, particularly for large-value banknotes which may be used as store of value.

Table 2 provides the estimates of the average and median banknote life using the Feige method. As expected, the larger-value banknotes have the longest life, with the INR500 and INR1000 circulating on average for 4 and 5.1 years, respectively, before being returned to the RBI for disposal. There is substantial variation, however, in the life of the banknotes over time.

Figure 6 plots the life of a banknote by denomination (excluding INR1000 notes) over time between 2003 and 2016. The variations in estimation of banknote duration are evident across methods, and the Feige method appears to provide more stable estimates of banknote life.[11] This is particularly the case for the highest value banknote (INR 1000), for which we provide a separate graph (Fig. 7). The results suggest

[11] As Rush (2015) argues, this is likely on account of the construction of Feige steady-state formula (Eq. 1), which only accounts for new banknotes when they are initially introduced. Furthermore, this method may also generate stable estimates if there is a regular flow of issuances of the same banknotes without any temporary withdrawal or bar on issuance of the same series (as is the case in our data for India).

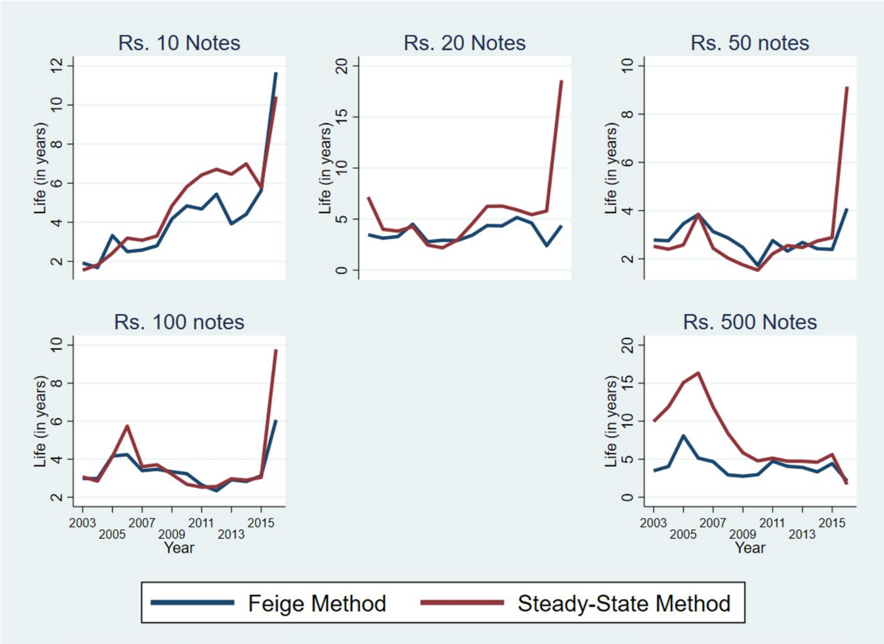


Fig. 6 Steady state and Feige method for life of banknotes

that there have been notable increases in banknote life for the lowest value banknote (INR10), whereas other denominations show a fairly stable duration of circulation over the period for which our data is available (2003–2016). Note that the spikes at the end of the graphs are likely on account of substantial changes to RBI focus on managing withdrawal of older banknotes and issuing new banknotes during the demonetization event.

Figure 7 suggests that there are wide variations in the life of INR1000 banknotes when measured by the traditional steady-state and the Feige method. For example, there is an abnormally large jump in the duration of circulation of these notes between 2003 and 2006. This was likely on account of very few disposals of high-value notes in these years (7.5 million pieces disposed, relative to nearly 500 million pieces in circulation). Thus, the traditional steady-state method generates noisy estimates in this regard.

Survival Analysis Results

To determine denomination-wise issuances for 2002, we compute the average share of each denomination to total issuances in the 5 years from 2003 to 2007,

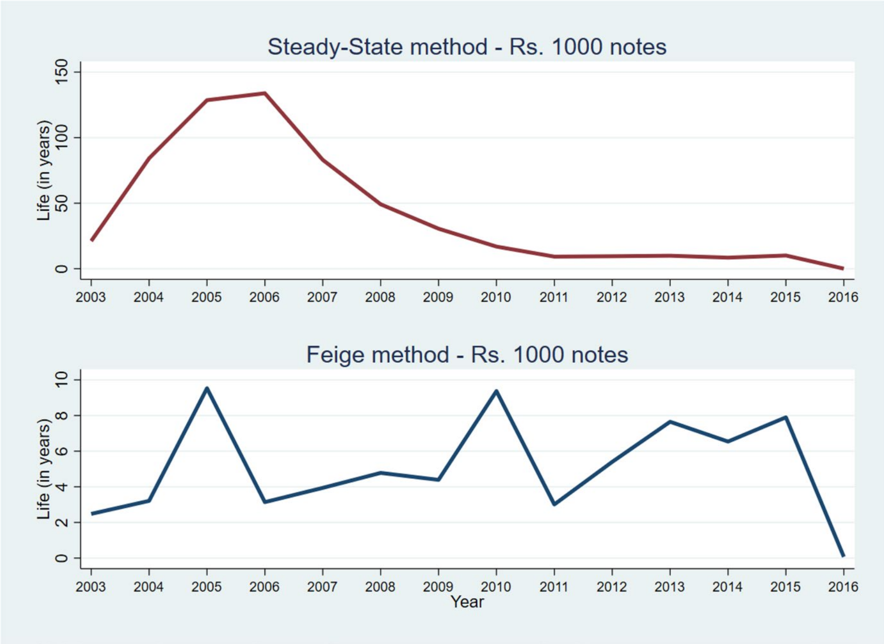


Fig. 7 Steady state and Feige method for life of INR1000 banknotes

and multiply total issuances in 2002 with these shares. While these shares do vary over time (Fig. 8), presenting some sensitivity to this choice of window, shares show low variability for lower denominations and appear, in the little data available, to mean revert within a 5-year cycle for higher denominations. We set the initial disposal values for 2002 to be zero as this is our initial period where banknotes are issued. Furthermore, data on ATM withdrawals was not available prior to 2011—we interpolated data using three-year moving averages for the period between 2011 and 2016 (prior to demonetization) to construct historical values for the velocity variable for the period between 2002 and 2010.

Overall, both Weibull and GG models are better suited to lower value denomination which have a median banknote life of around 4 or 5 years, suggesting that INR 10 and 20 meet this criterion.[12] In Fig. 8 below, the graphs show the expected quantity of surviving banknotes by denomination for the INR 10, 20, 50, and 100 banknotes. The red line represents the actual quantity of surviving banknotes, whereas the solid black line presents the estimated surviving banknotes from the GG model. The grey lines indicate the continuous disposal of surviving banknotes. This graph illustrates whether the fit of the model improves over time, which we could argue for

[12] It is important to note that the optimisation algorithm varies its parameter estimates and attempts to increase banknote life, resulting in a higher error for early issuances but lower for later issuances. Given that our time period is only 16 years, and the median banknote life is 5 years for INR 10 and 20 notes, it is possible that optimising to a unique solution may be a challenge, and result in these estimates.

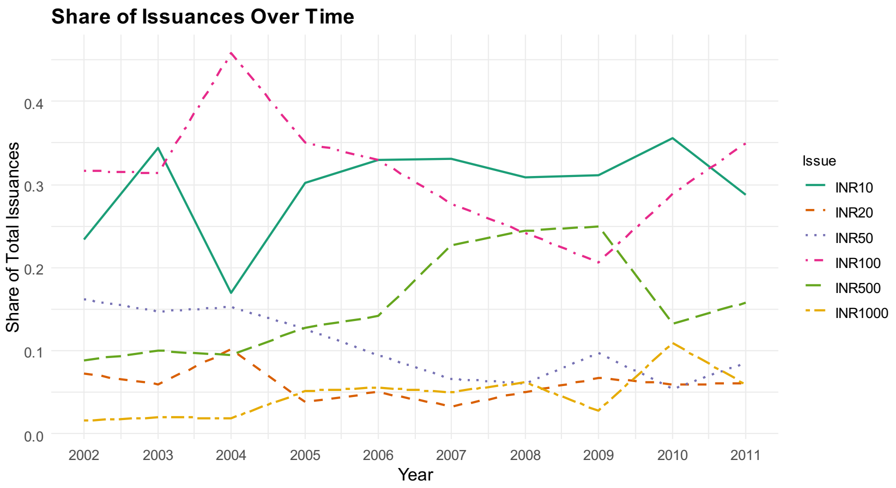


Fig. 8 Share of total issuance of each note over time

INR 10 and 20 to be the case, but we see little to no information from the estimates for medium-value banknotes (INR 50 and 100) from Fig. 8. The survival function here is based entirely on the data of net issuances for the period of analysis. Note that Fig. 9 is not necessarily indicating that the number of surviving INR 20 banknotes is increasing over time, instead it shows that the fit of the survival model (and the generalized gamma function) is improving over time for the INR 20 banknote. Thus, although the INR 10- and 20-rupee note are different denominations and therefore have differing issuance, use, and disposal patterns, our model is unable to fully account for these variations.

The corresponding graphs in Fig. 9 show that over time the number of surviving banknotes is increasing over the period of our analysis. As Aves (2019) mentions, it is also likely that these denominations are not typically the target of quality improvement programs, which is the case with the RBI as well.

The parameter estimates from the Weibull and GG models for INR10 and 20 are presented below in Table 3. Since the number of observations on which aggregate issuance data is available is low ($N=16$), parameter values as well as initial values are key to achieving model convergence.

First, the model diagnostic measures indicate that the GG model provides substantial efficiency gains in terms of estimating the model over the Weibull model. Although the Weibull model has only two parameters that need to be estimated (making convergence in a smaller sample easier), it generates estimates that are likely to be noisy. Thus, the GG model, although requiring a larger sample to converge, is able to model the survival function of banknotes marginally more efficiently (Aves 2019). The model diagnostics (RMSE and MAPE) indicate the goodness of fit of the model to the data—notably, the parameter estimates for INR10 and INR20 using a Weibull distribution do not vary at all, save for some changes in the standard errors. This suggests that Weibull models are unable to explain the life of

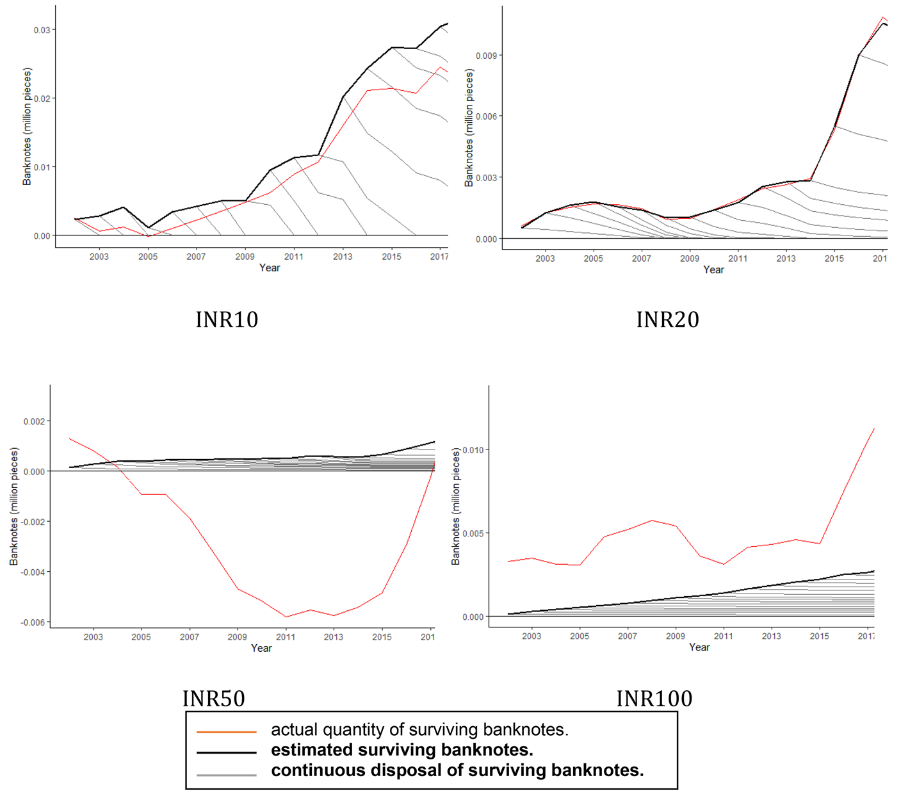


Fig. 9 Expected quantity of surviving banknotes (RBI annual data, by denomination)—generalized gamma function

a banknote using annual data accurately or meaningfully on net issuances from the RBI. Second, the results from the GG model differ between the two denominations, although the model parameters cannot necessarily be compared between them. In line with Aves (2019), we find a negative coefficient of the global financial crisis (GFC) on banknote wear and tear, and the results are statistically significant for the INR10 banknote. This suggests that prevailing macroeconomic conditions related to the GFC may have resulted in fewer transactions using INR10 notes, and therefore extended their life. In both INR10 and INR20 estimations, we find that greater velocity of circulation of cash exacerbates ageing of banknotes, but that this effect slows down with the passage of time (similar to the finding in Aves 2019). In a scenario unlike other countries where similar analyses have been conducted (Australia or Canada), the demand for cash is persistent in India, as we have seen from our past analysis (Tagat and Trivedi, 2020) as well as from the literature (Bhattacharya and Joshi 2001; Nachane et al. 2013; Raj et al. 2020). Thus, as there is greater

Table 3 Weibull and Generalized Gamma parameter estimates (2002–2018)

Weibull	INR10 Estimate	INR20 Estimate
Probability of survival	0.36	0.36
lambda	5.97	5.97
k	0.29	0.29
GFC	0.17	0.17
Currency in circulation	0.00	0.00
Velocity of circulation	−2.13	−2.13
Velocity × t	0.15	0.15
MAPE	536.40	666
RMSE	16,044.66	16,045
Generalized gamma	**INR10 Estimate**	**INR20 Estimate**
Location	3.48	17.91***
lambda	−0.01	0.21
k	6.10***	5.11
GFC	−0.07***	0.13
Currency in circulation	0.00	0.00**
Velocity of circulation	7.01***	30.46***
Velocity × t	−0.31	−1.23***
MAPE	117	4.9
RMSE	4055	129

Rows represent survival function parameters estimated on activity time as in Eq. (4). As noted in Aves (2019), the first three parameters (location, lambda, and k) indicate model fit to the data

MAPE mean average percentage error, *RMSE* root mean squared error, both indicators of model efficiency

$*p<0.05$; $**p<0.01$; $***p<0.001$

velocity of cash usage in a cash-based economy, INR10 and INR20 banknotes are likely to age faster and thus become more likely to be disposed within a specified time period. This is consistent with higher velocity, lower denomination banknotes suffering a large portion of wear and tear caused by inkwear and also due to their use in smaller-value transactions as a medium of exchange. Looking at parameter estimates of the survival function may yield preliminary insights about the life of these two lower-value banknotes. More work is needed to refine these estimates, including using higher frequency data which is not currently available. Estimates for the models of INR50 to INR1000 are less precise and come with much larger values of MAPE and RMSE. To show the fit of the models, we compare the predictions of both Weibull and GG distributions with the actual banknote (net) issuances data. This is presented in Fig. 10.

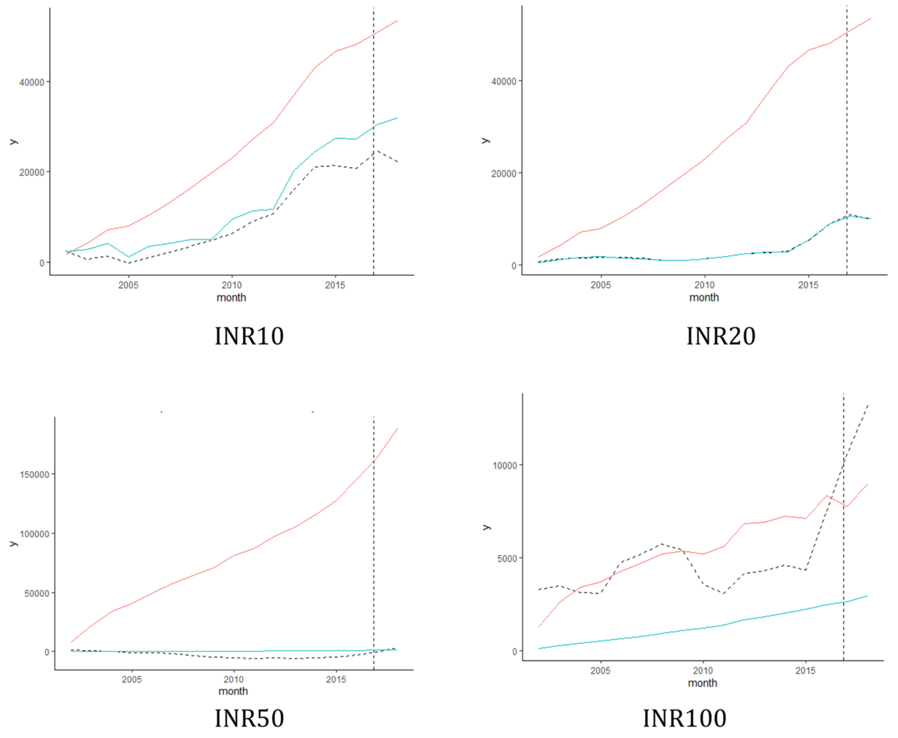


Fig. 10 Survival model results by denomination. The red line is Weibull model prediction, the blue line is GG model prediction, and the black line represents actual figures. The dotted vertical line is November 2016, when demonetization was implemented

Concluding Remarks and Implications for Policy

This paper has contrasted two traditional empirical approaches to estimating banknote life in India with a new statistical methodology utilizing duration modelling. The traditional steady-state (or turnover) methods provide a simple aggregate measure of the average duration for which an issued banknote remains in circulation until it is disposed. We find that higher value banknotes (such as the recently withdrawn INR 1000 note) have a median life of 5 years, and that medium-value banknotes, such as, the INR20 and INR50 banknote have a lower life span in circulation (3.4 and 2.7 median banknote life, respectively). However, this method relies on several simplistic assumptions regarding the circulation, velocity, and handling of banknotes. Given that demand for cash is persistent in India, it becomes important to address shortcomings in such analysis so that currency issuance and fitness policies can accordingly be framed. A third approach to estimating the life of a banknote is data-intensive and relies on parsimonious, publicly available data on denomination-wise currency issuances and disposals from the RBI's annual reports. Here, we use aggregate issuances and disposals data to model the life of a banknote using survival analysis models. There are several advantages of such statistical models over turnover methods: (a) we are able to relax the assumption that banknotes are disposed at a constant rate; (b) additional explanatory variables related to cash use and currency management can be incorporated in these models; and (c) we are able to derive precise estimates of banknote life over the period of time for which data are available. Naturally, survival analysis for banknote life estimation comes with its own set of limitations, which are specific to the context in which our analysis is executed (Aves 2019; Rush 2015). For example, we only have access to annual data over a period of 16 years, which makes our estimates grossly underpowered, and noisy for certain denominations, such as the INR10 where the median banknote life from turnover methods is approximately 4 years.[13] The parameter estimates for both the Weibull as well as the GG functions for certain denominations (such as INR100 and INR500) are uninformative and more data is needed to make meaningful estimations of banknote life for these denominations. It is also likely that these estimations are sensitive to assumptions on hoarding, where high-value banknotes are known to be associated with the shadow economy (Drehmann et al. 2002; Kumar 2016). The use of survival models in currency management applications is sensitive to the ability to optimize the aggregate fit of individual survival functions to the underlying issuance and destruction data. Other studies in this domain typically use monthly issuances data to model life of a banknote, and here it is important to note that our results are constrained by the annualized Indian data available in the public domain. The purpose of this exercise is to illustrate the utility of the survival analysis methods in estimating the life of banknotes for India, while acknowledging limitations and outlining avenues for future work. For the survival analysis, we set initial disposal values for 2002 to be zero as this is our initial period where banknotes are issued. This implies that we explicitly assume a "burn-in" period for issuance and disposal of banknotes based on data availability and not necessarily informed by theoretical or policy-based assumptions. Another major limitation of our analysis is the inability to distinguish between INR 10 and INR 20 using the Weibull function. Location refers to a parameter of the GG function that measures the fit of the survival function to the data. Since it is not statistically significant in any of the models, we cannot comment on its interpretation, and it cannot be compared across models either (Aves 2019). We do not have additional covariates to include in this model as lack of convergence due to low frequency data (and therefore small sample size) is a major barrier to incorporating additional insights.

In line with barcode tracking of banknotes in other countries, such as Canada, these models are more likely to be better equipped when using banknote-level data where available. Having access to monthly-level issuances and disposal data may help improve efficiency of the models and their fit to the data, especially since the

[13] Given the difficulties in estimating the model using imputed monthly data on issuances, we are not able to fully capture the heterogeneities in currency management and issuance related to the INR 10 note. We argue that this is largely on account of the large share of the Rs. 10 notes in the velocity of circulation prior to demonetization (primarily for transactions purposes). This is derived from the data that suggests Rs. 10 banknotes have seen a steady growth in issuance, but especially between 2011 and 2017. We cannot rule out the increasing use of digital methods for small-value transactions, but since our period of analysis predates the widespread adoption of UPI, we cannot pinpoint a cause here.

applications of survival analysis in banknote life estimation use such high-frequency data (e.g., Aves 2019). It is plausible to use interpolation to arrive at month-level issuance and disposals data, but this will need to account for seasonality as well as any other month-level changes in issuance policies (e.g., related to banknote distribution and delivery), which are likely to vary across India, given the breadth of the network of currency distribution. Furthermore, using a non-linear method of interpolation will be critical to ensuring that the model converges using this data, which might otherwise result in a singular gradient error. Our analysis also does not account for any minor changes in banknote production technology or issuance of new series with varying security features, as these are typically at the month-level. Future work should focus on incorporating more explanatory variables at the level of months to provide more explanatory power to the model estimates.

There are two implications for policy arising out of this first attempt to determine the quality and life of paper banknotes in India. First, lower-value banknotes have a far more stable life than higher value banknotes, although they are more frequently used and therefore have a shorter life. Since these estimates are more reliable, it is possible for RBI and other currency management stakeholders to consider what the 'ideal' life of a low-value banknote is so that it can continue to meet transactions and liquidity requirements in the heavily cash-dependent Indian economy. Furthermore, as Loizidou et al. (2022) note, there is much for banknote issuers and printers to gain from understanding the factors that affect cash life cycles. As India transitions from a cash-dependent to a less-cash driven payments landscape, the currency management function of the central bank must also adapt. For instance, in 2023, the INR 2000 note has also been withdrawn from circulation. With a relatively limited timespan in circulation (7 years), there is little that we can learn from studying life cycles of high-value banknotes that are not typically used for transactions purposes (Tagat et al. 2020). Even as smaller-value transactions become a mainstay of digital payment modes (such as UPI), there is much to learn from analyses of cash life cycles with more data as this study attempts, especially for the lower-value denominations (INR 10, 20, and 50). From the recent experience of demonetization, we know that there are challenges to ensuring prompt and timely availability of paper banknotes that may in turn constrain household financial liquidity (Karmakar and Narayanan 2020), and ultimately affect their welfare (Chodorow-Reich et al. 2020). Thus, regular issuance and prompt disposal of such notes may be critical to ensuring that there are no shortfalls in their availability for transactions purposes. Second, collating and maintaining higher frequency data on currency management (issuances, disposals, changes in design) in a systematic manner can aid in strengthening the life of a banknote estimates using the survival analysis framework. This can help central banks by providing feedback on any quality-improvement programs or any changes to ink or other banknote features that are aimed at enhancing the life of a banknote. For example, RBI has long since considered the introduction of polymer banknotes that are known to be impervious to inkwear and mechanical defects relative to paper banknotes. Indeed, much of the work on polymer banknotes suggests that, on average, their life is slightly longer than that of the paper currency notes (Rush 2015). An opportunity to explore this further would lie in conducting pilot issuances of polymer banknotes in a specific geographic territory and comparing the life of banknotes between these two variants. This would provide a useful decision-making benchmark for future banknote issuances.

Appendix

See Fig. 11.

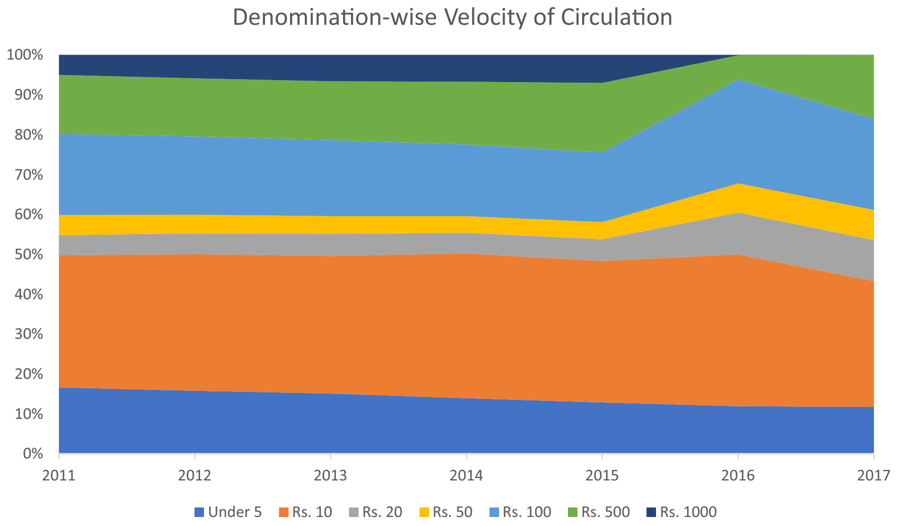


Fig. 11 Denomination-wise share in velocity of circulation (2011–2017). Authors' own calculations using cash withdrawn at ATM (volumes) data and denomination-wise circulation volumes data from RBI

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