Article II

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Economizing on Liquidity with Deferred Settlement Mechanisms

- Real-time gross settlement (RTGS) systems such as the Federal Reserve's Fedwire Funds Service enable participating banks to settle payments immediately and in the full amount; however, the high level of liquidity inherent in the systems requires large intraday credit extensions.

- An examination of several deferred settlement mechanisms that could potentially complement RTGS systems considers a novel mechanism—a receipt-reactive gross settlement system—that bases the settlement of a bank's payments on the value of its receipts over a given time, rather than on the bank's balance.

- The receipt-reactive mechanism can potentially reduce intraday credit extensions significantly while modestly delaying the average time of payment settlement; the mechanism also provides good incentives for banks to submit payments earlier in the day.

1. Introduction

On a typical day, the total value of payments settled by the Federal Reserve's Fedwire Funds Service exceeds $1.8 trillion. On average, credit extended to banks using Fedwire is about $30 billion over the course of the day, while the peak intraday amount reaches $86 billion. Given this high level of credit extensions, it is worthwhile asking whether payment settlements could be managed with a lower level of outstanding credit, thus allowing system operators to economize on liquidity.[1]

Fedwire operates as a real-time gross settlement (RTGS) system. RTGS systems transfer the full amount of payment orders between commercial bank participants immediately upon receipt, thus avoiding short-term debt obligations between participants. This is a desirable feature that has prompted many central banks worldwide to implement these systems over the past decade. However, because payment transfers between participants are made immediately in the full amount, and because of the asynchronous timing of payments by participants, maintaining the liquidity needs of RTGS systems can be costly. Indeed, some system operators have altered their RTGS systems in recent years to economize on the funds needed to complete settlements.

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One way to reduce a system's liquidity needs is by using deferred settlement mechanisms such as netting. In netting systems, payment orders are deferred until some designated time—usually late in the day—when the participants exchange only the net amounts they owe or are owed. If all participants successfully submit these net amounts, the system settles all the payments accumulated during the day with the least amount of funds possible—that is, just the net amounts. To achieve this economy in funds use, a netting system delays the settlement of payments so that all orders remain pending until the net settlement payments are completed successfully. This delay feature creates distinct liquidity and risk management characteristics.

Another type of deferred settlement mechanism queues payments as they enter the system. Some European RTGS systems use these "queue-augmented RTGS systems," or hybrid systems.[2] Such systems save on liquidity—as in a netting system—but with less delay than end-of-day netting imposes.

In this article, we propose alternative ways of settling payments submitted to the Fedwire Funds Service that would result in lower intraday credit extensions. We analyze the effects of complementing an RTGS system with various deferred settlement mechanisms by performing simulations on historical Fedwire data. Although others have studied the effects of such modifications on payments systems, this is the first examination in the context of Fedwire.

One function of a payments system design could be to minimize the combined cost of delaying payments and the risk of extending intraday credit to commercial banks—that is, the credit risk that a central bank assumes by providing intraday credit. We do not use an explicit, objective function to evaluate the various alternatives to an RTGS system because we do not know banks' preferences regarding delays or specific default risks. We can, however, evaluate those designs that reduce both delays and credit extensions as preferable to others. In short, some modifications may clearly be more effective than others but none compares easily with a pure RTGS system, which by definition eliminates delays. Our results suggest that, compared with RTGS systems, alternative settlement designs could significantly reduce credit extensions while modestly delaying the average time of settlement of payments.

This article is organized as follows. In the next section, we discuss the basics of deferred settlement systems, and in Section 3 we describe the systems used in our simulations. In Section 4, we describe the performance metrics and results of the basic simulations, and in Section 5 we conduct a sensitivity analysis of the results obtained from alternative levels of queued payments. Sections 6 and 7 present more detailed analyses of liquidity use and the level of end-of-day queues. In Section 8, we discuss our results and the likely behavioral responses by a bank participant to the availability of the simulated systems. We conclude with a discussion of our results in light of the previous literature.

2. Characteristics of Deferred Settlement

As a baseline case, a pure RTGS system is one in which no payments are deferred for settlement—all payments are released upon receipt by the system operator as long as the participant has adequate funds to settle the payments. If not, the payment is rejected. Deferred settlement can work in conjunction with RTGS systems. In practice, deferred settlement mechanisms can operate in many ways, but all require certain criteria by which payment orders are entered, ranked, and settled. In addition, criteria for the end-of-day closing or the emptying of queues are required in a queuing system.

The *entry criterion* in a deferred settlement mechanism determines whether payments are deferred or whether they are settled immediately by pure RTGS. This criterion can be based either on decisions made by participating banks or on an automatic feature created by prespecified criteria. In many European RTGS systems, deferment is automatic: Rather than reject payment orders outright, the systems automatically place payments in a queue if RTGS settlement of the payment would breach the credit limit of the participant.

The *order criterion* defines the ranking or ordering of payment messages that are queued. Most contemporary RTGS systems adhere to the first-in, first-out (FIFO) principle—that is, payments that enter the queue earlier have priority over payments that enter the queue later. The FIFO principle is easy to implement. Assuming liquidity constraints, FIFO performs reasonably well when a system's smaller payments are submitted generally earlier in the day. Because early, larger payments can obstruct FIFO-ordered queues, some RTGS

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systems now have "bypass-FIFO" algorithms that allow participants to reorder and prioritize queued payments. Some, such as the CHAPS Clearing Company in the United Kingdom, allow the participants to select the order of the queued payments according to other criteria, for example, by the value of the payments.

The *settlement criterion* defines the rules by which payment messages are released from the queue, triggering the flow of money from the payer's account to the payee's account. Payments can be released from the queue either individually or in groups. In most queuing arrangements, payments are released individually, but some systems employ "gridlock-resolution" algorithms that allow multiple payments to be settled from the queue simultaneously if the release of the payments on an individual basis is not possible (see Bech and Soramäki [2001, 2002]). In previously described queuing systems, the settlement criterion has been based on the balance of the participant—that is, payments are released as soon as the participant's balance is high enough to cover the payment's settlement. The release of payments from the queue can be based on other criteria as well. In this article, we propose a novel deferred settlement mechanism that bases the settlement of queued payments on the value of incoming payments rather than on a participant's account balance.

The last important element of the design of a queuing system is *end-of-day close of queues,* or how to "empty" the queue of payment orders at the close of business. One method used in some European systems is to settle all messages remaining in the queue after a certain length of time through an exchange of the net amounts of the payments. An alternative method of closing queues is to return unreleased payments to banks before the RTGS system closes so banks can redirect the unreleased messages to the RTGS system.

3. System Designs

In our simulations, we design a system in which payments go through one of two alternative channels—deferred settlement or real-time gross settlement. These two main channels recognize that some payments are more time-critical than others. Banks would likely want to settle their time-critical payments through the immediate RTGS channel while the less time-critical payments could go through the deferred settlement channel to save liquidity. The deferred settlement channel allows payments to take one of three possible paths: a one-hour netting system, a six-hour netting system, or a unique type of system that we call a receipt-reactive gross settlement (RRGS) system.

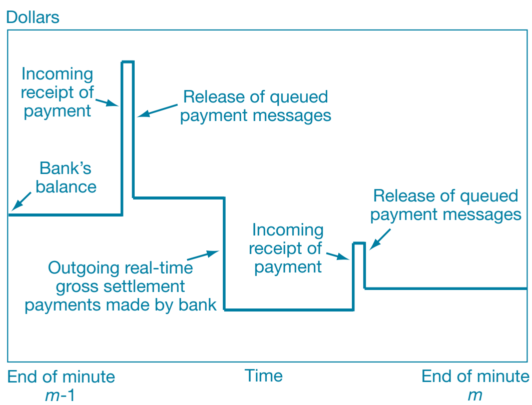
3.1 Receipt-Reactive Gross Settlement System

In the receipt-reactive gross settlement system that we simulate, a portion of banks' payments is randomly selected to be settled through RTGS, while the remaining set of payments is placed in a queue for deferred settlement. Queued payment messages are ranked on a first-in, first-out basis. For the release criterion, a payment message's release from the queue is triggered by the arrival of incoming funds received by the bank within a specified period of time. In our simulations, this time period is one calendar minute.[3] The system will release within one minute as many payments from the front of the queue as possible to offset—but not exceed—the amount of incoming funds. In the simulations, this process continues throughout the day until 5:30 p.m., when the queue closes. The exhibit below shows the effects of a receipt-reactive queue on a bank's balance during a minute in which the bank both sends and receives RTGS payments (see Appendix A for a detailed description of this queuing system).

An important design element of a queuing system is how to "empty" the queue of payment messages at the end of the day. In our simulations, we randomly reassign the unreleased payments a settlement time between 5:30 p.m. and 6:00 p.m. This is our approximation to returning, at 5:30 p.m., the unreleased (that is, unsettled) payments to the banks that submitted them, with the banks subsequently resubmitting the payments through the RTGS system over the next half-hour.

This feature of our queue design was chosen for a number of reasons. The end-of-day return of the queued messages is consistent with the basic design of queuing systems used as adjuncts to RTGS systems. The receipt-reactive queuing system

Dynamics of a Bank's Balance under Receipt-Reactive Gross Settlement



is intended to encourage banks to submit to the queue those payments that can be settled with incoming funds. If particular payments cannot be settled that way, then the banks would likely submit the payments through the RTGS system, which is designed to settle payments immediately with available balances. Therefore, returning banks' payments that remain in the queue to the respective banks near the end of the day is consistent with the intended use of the receipt-reactive queue and of the RTGS system.

3.2 One-Hour and Six-Hour Netting Systems

We simulate the performance of two simple netting systems. In both systems, a portion of all payments is settled by RTGS while a complementary set of payments is put in a queue. The queued payments are cumulated for a certain period of time, netted, then settled—even if they cause an overdraft in the banks' account balances. In the first simulation, the payments are cumulated, netted, then settled after each hour of the operating day. In the second simulation, cumulated payments are netted and settled after six hours. (See Table 1 for a summary of the simulations.)

4. Simulations of the Three Systems

To gauge the usefulness of these three complements to RTGS systems—one-hour netting, six-hour netting, and receipt-reactive gross settlement—we simulate their performance using a program developed by the Bank of Finland. The simulator is described in detail in Leinonen and Soramäki (2003). (See also the Bank of Finland's website: <http://www.bof.fi/sc/bof-pss>.)

In the simulations, we initially assume that banks would submit half of all individual payments to the queue for deferred settlement and the other half of their payments to the RTGS system. In the simulations, we include all Fedwire funds transfers for a randomly selected set of ten days between October 1999 and February 2000. We perform a sensitivity analysis (see Section 5) and present robustness checks to gauge the effects resulting from different levels of participation in the three deferred settlement arrangements. Using three days of data, we reproduce the simulations with either 20 percent or 80 percent of all payments assigned to the deferred settlement mechanism. The simulations are conducted on historical payment transactions similar to the generalized example below:

Sender Account Number	Receiver Account Number	Value Sent (Dollars)	Submit Time (Hour:Minutes)	Routing Flag
02100xxxx	02100yyyy	100.50	10:20	1 or 0

Table 1

Summary of Simulated Systems

System	Entry Criterion	Order Criterion	Release Criterion	End-of-Day Close of Queue
One-hour netting	Randomly selected 50 percent of payment orders. In conducting our sensitivity analysis, we randomly selected either 20 percent or 50 percent of payments.	Not applicable	All payment orders for all banks in queues are netted and released at *one-hour* intervals.	All payment orders in queue are netted at 6:30 p.m., the end of the Fedwire day.
Six-hour netting			All payment orders for all banks in queues are netted and released at *six-hour* intervals.	
Receipt-reactive gross settlement		First-in, first-out	A payment order at the front of a bank's queue is released from queue as receipts for the bank, within a calendar minute, exceed the value of the payment order to be released.	Any payment orders remaining in queues at 5:30 p.m. are randomly and uniformly assigned and settled by real-time gross settlement over the next thirty minutes.

In this example, Bank A (with American Banking Association account number 02100xxxx) sends Bank B (02100yyyy) $100.50 at 10:20 a.m. through the Fedwire service. If the routing flag is one, the payment is routed to the deferred settlement mechanism. If the flag is zero, the payment is routed to the RTGS system. The routing flag randomly assigns a one or a zero according to a predetermined level of participation in the deferred settlement mechanism (for example, 20 percent, 50 percent, or 80 percent of the day's payments have routing flags equal to one). For any given day, several hundred thousand transactions are routed, one by one in the order of their time stamps, to the settlement mechanism assigned. If routed to RTGS, a payment will be settled immediately. If routed to the deferred settlement mechanism, settlement could be delayed. We report the detailed results of these simulations in Appendix B.

Our primary performance metrics focus on the system's impact on daylight overdrafts and on the delay in the time of payment—that is, the difference between the time the payment was submitted and the time it was settled.

4.1 Daylight Overdrafts and Delay Indicators

A bank incurs a daylight overdraft when its balance falls below $0. The Federal Reserve measures daylight overdrafts outstanding at the end of each minute of the Fedwire operating day and reports the aggregate peak and average overdrafts for all banks. The aggregate *peak overdraft* occurs in a specific minute in which the aggregate overdraft has the highest value of all the minutes in the Fedwire operating day; the *average overdraft* is the sum of all the banks' overdrafts for all minutes of the day divided by the number of minutes in the Fedwire operating day. We focus on the average overdraft because that is the basic measure used by the Federal Reserve to calculate the fees it charges banks for their credit use, which is inherent in daylight overdrafts (see Appendix C for a description).

The basic indicator of delay that we consider is the *average time of settlement* across all payments and banks. It is the average time at which payments settle—where the time of actual settlement is weighted by the value of the payment.

The *delay statistic* is a standardized indicator that may take values between zero and one. RTGS, with its immediate settlement, results in a zero-delay statistic. End-of-day netting results in a delay statistic equal to one. In comparison with the average time of settlement statistic, the delay statistic tends to weight more heavily payments that are entered early in the day, even if the payments are small in value.

We compare the three simulated queue-augmented RTGS systems with Fedwire's historical performance using these liquidity and delay metrics (Table 2). We find that only the receipt-reactive gross settlement system reduces the use of overdraft liquidity by a statistically significant amount. While the two netting systems affect the average overdraft, neither of these differences is statistically significant (see Appendix B).

The one-hour netting mechanism shows no statistically significant change in the average overdraft relative to RTGS. Payments are delayed the least under one-hour netting, with the average time of settlement of payments moving to 2:51 p.m. from the RTGS average time of 2:35 p.m. For six-hour netting, the decrease in overdrafts is higher (although it is not statistically different from no change), but so is the delay in payments, as the average payment time moves to 3:46 p.m.—the latest time of all the alternatives. The receipt-reactive gross settlement system reduces average overdrafts by about 14 percent—the largest amount among the alternatives considered here. The time of payment is 3:18 p.m., slightly later than for the one-hour netting alternative. The average time of settlement increases by seventy-one minutes for six-hour netting while it increases by forty-three minutes for the receipt-reactive queuing system—a 65 percent difference—while six-hour netting shows a 150 percent increase in the delay statistic when compared with the receipt-reactive system. Our results suggest that the receipt-reactive system performs markedly

Table 2

Averages from Simulations with 50 Percent Participation

Treatment	Average Overdraft (Billions of Dollars)	Percentage Change from RTGS	Peak Overdraft (Billions of Dollars)	Percentage Change from RTGS	Average Time of Settlement	Delay Statistic (Percent)
Real-time gross settlement (RTGS)	20.29	—	66.28	—	14:35	0
One-hour netting	20.41	0.58	64.69	-2.40	14:51	7.53
Six-hour netting	19.45	-4.10	60.15	-9.25	15:46	34.35
Receipt-reactive gross settlement	17.52	-13.64	72.66	9.62	15:18	13.74

Source: Authors' calculations, based on data from Federal Reserve Bank of New York, Fedwire Funds Service.

better in settling early-morning and early-afternoon payments, as well as smaller ones.

The receipt-reactive queuing system's increase in peak overdrafts, in conjunction with its decrease in average overdrafts, is a bit puzzling (Table 2). Why do peak overdrafts increase if payments remain in the queue until sufficient receipts arrive for the bank? The answer is related to the current timing of payments on Fedwire. As described in McAndrews and Rajan (2000), a high proportion of the value transferred over Fedwire occurs in the late afternoon. During that period, banks have a large number of payment receipts, as well as payment outflows. Under the receipt-reactive gross settlement system, the high level of receipts that occurs during the late afternoon (from the 50 percent of payments that continue to be settled through the RTGS system) begins to trigger the release of a large number of queued payments. That process cascades as the payments released from the queue are receipts for other banks, which triggers further releases from the queues. For many banks—primarily large banks—the outflow from the queue "absorbs" all of the bank's receipts. Few, if any, of its receipts at that time of day add to its balance; instead, the receipts facilitate the release of payments from queues. The combination of receipts being dedicated to the release of payments from the queue and the submission of many RTGS payments at that time of day drives many accounts deeply into overdraft. Smaller banks, not having the same heavy outflow of payments, enjoy significantly more positive balances at that time, as the cascade of payments occurs. On balance, this process further concentrates payment activity in time, and reduces the use of overdrafts on average, even though the peak overdraft is increased. Of course, we would expect that banks would alter their behavior if they expected such a cascade of payments to be triggered.

> *Our results suggest that the receipt-reactive system performs markedly better in settling early-morning and early-afternoon payments, as well as smaller ones.*

5. Sensitivity Analysis

To test the robustness of our results, we examine two simulations in which 20 percent and then 80 percent of payments are randomly selected for deferred payment. These simulations were conducted on three days of data. Because an analysis of only three days yields such a small sample, we do not consider statistical significance, but simply report averages.[4]

One potential problem with a receipt-reactive gross settlement system is that banks may make an excessive number of submissions to that system and very few to the RTGS system. If all banks find it convenient and economical to submit payments to the queue for deferred settlement, then a paucity of RTGS payments might cause widespread payment delays.[5] By varying the number of payments submitted for deferred settlement, we can evaluate how each of the alternative systems would perform, assuming different behavioral patterns (see Table 3 for the results of these simulations). The numbers for the RTGS system are calculated using only the three days pertinent to the alternate level simulations and thus differ from those in Table 2.

These simulations suggest that our results are relatively robust at different levels of participation.

The level of liquidity savings and the length of delays in settlement increase as more payments are submitted to the queues. Of interest is the result that the RRGS system maintains comparable or higher levels of liquidity savings for a given delay than does the six-hour netting system, at all levels of submission to the queue. In addition, even with 80 percent of payments submitted to the queue, the RRGS system imposes an average settlement delay that is no greater than the delay with six-hour netting. However, the important difference is that RRGS does this with much greater liquidity savings than six-hour netting does. The delay statistic provides some evidence for why this occurred. The average time it takes to settle a payment for the 80 percent receipt-reactive system is one minute more than the average time for six-hour netting, suggesting that the receipt-reactive system holds more large payments in its queue until the end of the day. The delay statistic for six-hour netting is about 2.5 times higher than the statistic for the receipt-reactive system, indicating that the RRGS queue outperforms the six-hour netting system in overdraft management.

Table 3

System Averages Comparing Alternate Levels of Participation

Treatment	Average Overdraft (Billions of Dollars)	Percentage Change from RTGS	Peak Overdraft (Billions of Dollars)	Percentage Change from RTGS	Average Time of Settlement	Delay Statistic (Percent)
Real-time gross settlement (RTGS)	20.52	—	68.49	—	14:32	0
One-hour netting						
20 percent	20.37	-0.74	67.16	-1.93	14:37	2.52
50 percent	20.55	0.12	65.27	-4.69	14:47	7.31
80 percent	19.83	-3.38	64.66	-5.59	14:53	9.93
Six-hour netting						
20 percent	20.53	0.04	64.42	-5.94	15:01	13.97
50 percent	19.87	-3.16	62.50	-8.74	15:45	34.89
80 percent	17.32	-15.59	50.77	-25.87	16:28	55.44
Receipt-reactive gross settlement						
20 percent	20.88	1.75	71.47	4.36	14:48	3.35
50 percent	17.38	-15.33	70.40	2.80	15:18	14.78
80 percent	11.49	-44.05	55.92	-12.52	16:29	22.50

Source: Authors' calculations, based on data from Federal Reserve Bank of New York, Fedwire Funds Service.

5.1 Liquidity

To provide more insight into the performance of these deferred settlement systems, we need to understand how the mechanisms use liquidity throughout the day. While our initial analysis focused on the mechanisms' effects on overdrafts and delays, we now look at four measures of liquidity, assess their levels in each system, then compare the levels with those found in the RTGS system (see Appendix B for further details).

The *average funds transfer* statistic measures the average level of liquidity, or funds, that must be transferred from an individual account from one minute to the next, across the minutes of the day, to complete the payments for the day. For example, in the RTGS system, the average funds transfer for an account is $226,000 per minute. To make this transfer, the bank must have sufficient funds in its account or receive sufficient funds from other banks. For any bank in the system, the average funds transfer may take values between zero and the per-minute gross value of payments sent by the bank.

In general, netting exhibits lower average liquidity usage over the day as indicated by the average funds transfer measure compared with an RTGS or RRGS system. Once queued, payments must stay in the queue until the next net settlement time and do not cause any balance changes in the interim. This liquidity conservation increases with longer netting times and larger participation in the netting systems (Table 4).

If we look at the minute with the highest average funds transfer, we obtain the *maximum funds transfer*. Using this indicator, we see that the netting systems demonstrate very high liquidity requirements during their net settlement periods—up to $17 million. These one-minute maximums occur near the end of the day when the Federal Reserve's RTGS system experiences its usual peak in volume. The receipt-reactive gross settlement system, however, produces lower maximum liquidity outflows, demonstrating its ability to smooth the liquidity usage over time. This smoothing—a feature of the more dynamic receipt-reactive queuing mechanism—results in greater average liquidity usage than the netting alternatives, but also produces significantly smaller maximum requirements. The lower maximum requirements are important as it is generally less costly for banks to make small payments that are distributed throughout the day than to

The receipt-reactive queue acts to smooth the liquidity usage across the payments system participants and across the day.

Table 4
Liquidity, Correlation, and Skewness Results

Treatment	Average Funds Transfer (Thousands of Dollars)	Maximum Funds Transfer (Thousands of Dollars)	Correlation with RTGS Balances (Percent)	Skewness
Real-time gross settlement (RTGS)	226	2,206	100.0	—
One-hour netting				
20 percent	209	5,521	99.5	13.9
50 percent	170	10,808	98.0	18.8
80 percent	130	13,901	97.2	23.4
Six-hour netting				
20 percent	201	10,944	96.2	20.3
50 percent	145	12,122	90.5	23.2
80 percent	86	17,356	84.7	19.0
Receipt-reactive gross settlement				
20 percent	209	1,827	94.8	13.0
50 percent	165	1,975	86.6	26.2
80 percent	140	3,315	76.0	24.2

Source: Authors' calculations, based on data from Federal Reserve Bank of New York, Fedwire Funds Service.

make large payments. The smoothing effect of the RRGS system is thus a desirable feature.

The *correlation with the RTGS* measure represents the degree of correlation and hence the exhibited independence between the end-of-minute balances of RTGS and the other simulated systems. The one- and six-hour netting mechanisms exhibit a greater correlation between their balances and the original balances created by the RTGS system, despite the netting systems' lower average figures of liquidity use. The lower correlation for RRGS indicates that, while it results in higher balance transfers than the netting systems throughout the day, these balances are circulated more rapidly, allowing earlier settlement of payments and a greater divergence in the pattern of balances from the original RTGS balances.

The *skewness* measures the positive differences in a bank's balances from an RTGS system across the minutes of the day. This measure is obtained by calculating the skewness of the balance differences between RTGS and the simulated system. When compared with the netting systems, the receipt-reactive gross settlement system's distribution of the differences in balances is more positively skewed, suggesting that more participants maintain positive balances—and hence a reduced need for overdrafts on average. The receipt-reactive queue acts to smooth the liquidity usage across the payments system participants and across the day, generating larger balances and smaller overdrafts from the system's liquidity.

6. End-of-Day Queue Analysis

When looking at the simulated receipt-reactive gross settlement system, it is important to determine how the end-of-day settling of payments influenced our results. The RRGS system closed at 5:30 p.m. and the remaining payments were evenly disbursed over the next thirty minutes. Table 5 gives the percentages of all payments submitted to the queue that settled by 5:30 p.m. In addition, the table presents the average value of payments in the queue at 5:30 p.m. to offer a sense of the role that size played in the settlement of these queued payments.

The one-hour netting arrangement quite naturally yields the best results here because the payments in the queue only start accumulating from 4:30 p.m. Because this time of day experiences the largest value payments (McAndrews and Rajan 2000), the average payment values are twice as high as those produced by six-hour netting and RRGS. The six-hour netting system shows that payments entered as early as 12:30 p.m. remain in the queue, which results in a low percentage of settled queued payments by 5:30 p.m. In terms of overall settlement by 5:30 p.m., the RRGS system performs similarly to a one-hour netting system at the 20 percent and 50 percent participation levels and more like a six-hour netting system at the 80 percent level. This result indicates that when 80 percent of payments are deferred to RRGS, many never get settled and are returned to the banks that sent them.

Table 5

Queue Characteristics at 5:30 p.m.

Treatment	Queued Payments Settled (Percent) Value	Queued Payments Settled (Percent) Volume	Average Payment Value in Queue (Thousands of Dollars)
One-hour netting			
20 percent	73	91	10,234
50 percent	69	90	10,653
80 percent	73	91	10,063
Six-hour netting			
20 percent	25	41	4,338
50 percent	26	40	4,291
80 percent	25	41	4,310
Receipt-reactive gross settlement			
20 percent	64	73	4,533
50 percent	72	80	4,890
80 percent	28	48	5,184

Source: Authors' calculations, based on data from Federal Reserve Bank of New York, Fedwire Funds Service.

A feature of the simulated RRGS mechanism is that the FIFO rule was strictly adhered to when settling queued payments. The FIFO rule results in situations where large payments in front of the queue block smaller payments from being settled. The average value of queued payments at 5:30 p.m. was considerably higher for all levels of payments queued. The value of payments remaining in the queue rose as the participation in the queue increased. At the 80 percent level, the average value of payments that remained queued was 50 percent higher than the average value of payments in the original RTGS system ($3.45 million). This result suggests that the performance of RRGS systems could likely be improved by using a different order criterion, such as allowing smaller payments to go first, splitting the large transactions into several smaller ones, or using gridlock-resolution mechanisms.

7. Discussion of Simulation Results and Likely Behavioral Responses

Netting has long been acknowledged as an efficient way to reduce the liquidity needs of a payments system. Roberds (1993) shows that the netting of payments achieves the theoretical minimum of liquidity use for the settlement of a specific set of payments. Another way to reduce liquidity needs is to use various queuing arrangements in RTGS systems.

Many simulation studies of the behavior of queue-augmented RTGS systems have been conducted recently. The research examines the mechanical reordering of payments that is possible with a queuing system and then compares this feature with other alternative designs to see how each handles liquidity use and payment delays. Koponen and Soramäki (1998) and Leinonen and Soramäki (1999) use the simulation approach to measure the liquidity savings and settlement delays for a number of alternative queuing, netting, and payment-splitting techniques with an RTGS system using data from the Bank of Finland's RTGS system. Both studies conclude that queuing systems can contribute substantial improvements compared with pure netting systems. Bech and Soramäki (2001) analyze the effects of a simultaneous settlement algorithm based on FIFO to settle a subset of payments from queues.

A report on RTGS systems by the Bank for International Settlements (1997) discusses how to sequence payments so that incoming transfers from other banks can be used to fund payments. A pure RTGS system relies solely on the participants (in a decentralized way) to time their payments in a manner that best utilizes their incoming funds.

Our simulation results show that netting in conjunction with RTGS settlement is not very desirable. Netting every six hours yields relatively modest but statistically insignificant reductions in daylight overdrafts (3.2 percent) compared with a significant delay in payment timing (one hour and thirteen minutes in average settlement time). Compared with one-hour netting, the settlement delays in six-hour netting are much greater. The simulated RRGS mechanism outperforms the netting systems when both liquidity savings and payment delays are taken into account. The receipt-reactive system saves significant liquidity (13.6 percent) and results in relatively modest payment delays (forty-three minutes) when compared with six-hour netting. These results are in line with those of the studies cited above.

7.1 Bank Participation and Risk

One question to ask is whether banks would actually use deferred payment mechanisms if they were available. Our simulations cannot predict banks' behavior. However, by relying on how the mechanisms work in a simulated environment and applying theoretical reasoning from the models of payment behavior, we can gain insight into the likely endogenous responses to implementing these complements to an RTGS system.

Consider the netting systems, for example. The simulation shows that a netting system that settles payments each hour of the day, even if it were to attract 50 percent of the payments on Fedwire, would not create a statistically different level of daylight overdrafts. When we consider the *participation risk* in a netting system, it is unlikely that banks would use such a facility.

Participation risk is present in many netting systems. In the operation of most payments systems, if a bank enters payments into the system, the bank is expected and, in some cases, obligated to settle those payment orders. If the bank expects many offsetting payments to be entered, but in fact only a few are, the bank may face a larger-than-expected settlement obligation. Netting systems tend to be more effective in gathering offsetting payments as more banks participate. Hence, a start-up netting system exposes potential participants to risk. If many banks participate, the bank will have a small expected settlement obligation, but if only few others do, the bank may have a larger-than-expected settlement obligation.

If a payments system were to offer a netting arrangement in conjunction with an RTGS system, banks that choose to use the netting mechanism would face liquidity risks. Those banks that use the netting system may end the day needing more liquidity than if they had carefully managed their payments strictly through an RTGS system. RTGS system participants likely submit payments in ways meant to lessen their liquidity demands and risks endogenously. As a result, a netting service might fail to attract participation when offered in conjunction with the current Fedwire service.

Deferred settlement systems provide a means to allow participants in an RTGS system to make some payments *contingent* on the submission of offsetting payments by their counterparties. Allowing a participant's payment submission strategy to be contingent on the payment submissions of others reduces the risk of loss associated with making payments and the risk of having one's counterparties fail to make expected offsetting payments prior to defaulting. The reduction in that risk should lessen the incentive to delay submitting one's payments, at least in the contingent, deferred settlement payment option.

We expect that banks would face lower participation risk in the receipt-reactive queuing system. The basic operation of the queue is useful to a single bank in isolation, even if no other banks use their options to queue payments. Queuing enables the bank to automatically synchronize outgoing payments with its incoming payments. This is an important advantage in encouraging use of the queue: Banks face no risk of increasing their liquidity demands by using the queue. They can always do at least as well for themselves by using the queue to manage their liquidity demands as they would if they had their own in-house automatic queue management system.

How would the banks change the timing of their payments to the system in the new environment? Models of the timing of payments in an RTGS model have been presented by Angelini (1998, 2000), Buckle and Campbell (2002), Kobayakawa (1997), and Kahn, McAndrews, and Roberds (2003). Some of these studies consider the default risk of counterparties and focus on the possibility of payment delays in an RTGS system, partly because of the risk of sending the gross amount of a payment to a counterparty in advance of receiving an offsetting amount from that counterparty. Because payments made in an RTGS system are not contingent on the submission of payments by counterparties, banks could be reluctant to submit payments in a timely fashion, and as a result, the timing of all payments could be delayed (relative to the time that a central planner would choose to have the payments sent). Buckle and Campbell (2002) consider requirements, chosen jointly by the participants, that commit participants to submit certain percentages of their payments by certain times of the day. Such a requirement is in effect in the U.K. payments system, CHAPS, and, on the European level, guidelines issued by the European Banking Federation govern the timing of payments in the TARGET system.

By using a receipt-reactive queue, banks would not face any downside risk to their liquidity position by the early entry of payment messages in the queue.

Recent theoretical work by Bech and Garratt (2003) analyzes the incentives that banks have in an RTGS system—in the case in which there is no default risk among counterparties—to coordinate the timing of payments. In their model, banks wish to complete a set of payments while economizing on their holdings of overnight balances. Bech and Garratt find that banks are expected to synchronize the timing of their payment submissions to take best advantage of incoming transfers, which allows all the banks to economize on their holdings of overnight balances. McAndrews and Rajan (2000) present evidence consistent with that model for the Fedwire system.

The receipt-reactive queue mechanism can be a useful way for a bank to reduce its demand for costly liquidity. In fact, we would also expect banks to enter more of their day's activity earlier in the day, with much of it placed in the queue. We expect this to be the case because in most RTGS systems today, a bank's only method of liquidity management is simply to delay payments. In contrast, by using a receipt-reactive queue, banks would not face any downside risk to their liquidity position by the early entry of payment messages in the queue because the amount released from the queue would always be less than the incoming payment amount.

In the United States, some banks use the Clearing House Interbank Payments System, which has liquidity-saving features. The presence of such a system could serve to satisfy banks' demand for an alternative to RTGS. If that is so, then appending liquidity-saving features to the existing RTGS system may not lead to a great deal of use of the liquidity-saving features.

The primary reason why a receipt-reactive system would generate good incentives for the early submission of payments is that the release of payments from the queue is independent of the timing of a *bank's own* RTGS payments. Because an RRGS system does not rely on a bank's balance, but only a bank's receipts to trigger the release of payments, the history of a bank's submission of RTGS payments does not affect the release of its payments from the queue. As a result, there is no incentive to delay making RTGS payments to allow the release of queued payment messages. This situation results in incentives for earlier entry of RTGS payments, which would endogenously improve the circulation of liquidity, releasing the queued messages of others in a virtuous circle.[6]

Some degree of transparency of the queues might also offer banks information that they cannot gain by using internal queues. With the use of such features, we would tend to expect widespread participation of banks in queuing mechanisms. In this case, gridlock resolution—which requires a central queue—could be used to optimize further the queue's performance.

Finally, centralized queuing in general may be beneficial for smaller banks. While larger banks currently time the entry of their payments into RTGS systems with the aid of internal queues, the operation of the receipt-reactive queue would give more banks the option of automated payment settlement.

8. Conclusion

In this article, we simulate deferred settlement mechanisms to understand the liquidity implications of using the mechanisms to complement real-time gross settlement systems. Using historical data on all payments made over ten days on the Fedwire Funds Service, we simulate two different netting systems and a receipt-reactive gross settlement system.

We find that, unlike an RTGS system, both netting and RRGS queuing systems introduce delays to payments. However, both netting and queuing also have the potential to reduce—in some cases, significantly—daylight overdrafts. These results appear to be robust to alternative assumptions about the level at which banks are willing to submit payments to a queue for deferred settlement.

The receipt-reactive gross settlement system we examine is novel in that it releases payments from the queue based on a bank's receipts over a given time rather than on its balance. The simulations in this article indicate that an RRGS system reduces significantly more overdrafts than a six-hour netting system would, with considerably less delay in payments.

Our consideration of the receipt-reactive gross settlement system reveals that it may provide good incentives for banks to submit payments early to the queuing system, as the release of payments from the queue is independent of the submission of the bank's own RTGS payments. This feature is likely to encourage banks to quicken the timing of payments and to reduce the number of daylight overdrafts. As a result, such a system might prove to be a true liquidity-saving complement to an RTGS system.

While simulations provide a good starting point for studying enhancements to RTGS systems, our results suggest that these systems warrant further investigation. For example, how banks would change their behavior when offered these alternatives to payment settlement remains an open question. Going forward, a better theoretical and empirical understanding of banks' payment behavior would help inform policymakers considering enhancements to RTGS systems.

Appendix A: Detailed Dynamics of the Receipt-Reactive Gross Settlement System

In this appendix, we explain the features of our proposed receipt-reactive gross settlement design. A real-time gross settlement (RTGS) payment from bank i to bank j entered at time t is p_{ij}^{t}. Similarly, a queued payment message is $q_{ij}^{t'}(r)$, with t' denoting the time of entry in the queue and r denoting the message's rank in the order of its entry. A bank's funds balance at time t is denoted b_i^t. A settled payment is s_{ij}^{t}, where a settled payment is either an RTGS payment or a queued payment message that has been released at time t.

The basic receipt-reactive gross settlement design operates as follows: By the end of minute m, the payment messages $\{q_{ij}^{t'}(r): j \neq i, t' < m, r = 1, 2 \ldots, k\}$ are released from the queue, where k is the maximum rank that satisfies inequality A1:

(A1) $$\sum_{(m-1) < t \leq m} \sum_{j \neq 1} (s_{ji}^{t}) \geq \sum_{r=1}^{k} \sum_{j \neq i} (q_{ij}^{t'}(r)).$$

At the beginning of each minute, the rank of queued payments is reset so that the oldest queued payment is assigned rank one, the second-oldest, rank two, and so on. (The actual algorithm releases payments within the minute as soon as sufficient receipts arrive.)

Inequality A1 states that the first k queued payment messages of the bank are released in minute m when the value of the bank's receipts in that same minute are greater than or equal to the value of the k payment messages to be released. A bank's balance at the end of minute m will then be equal to:

(A2) $$b_i^m = b_i^{m-1} - \sum_{(m-1) < t \leq m} \sum_{j \neq i} (p_{ij}^{t}) + \left(\sum_{(m-1) < t \leq m} \sum_{j \neq i} (s_{ji}^{t}) - \sum_{r=1}^{k} \sum_{j \neq i} (q_{ij}^{t'}(r)) \right).$$

Equation A2 states that a bank begins a minute with its balance of the previous minute, and its balance decreases in the minute by any RTGS payments it makes and increases by the net amount of its receipts, less any release of payments from its queue. By inequality A1, the net amount of its receipts must be at least as large as the amount that is released from the queue. If a bank's queued payments were numerous and finely divisible—so that the receipts are approximately equal to the amount released from the queue—then the bank's balance would be approximately equal to its previous balance minus its outgoing RTGS payments: $b_t^m \approx b_t^{m-1} - \sum_{(m-1) < t \leq m} \sum_{j \neq i} (p_{ij}^{t})$.

In a theoretical limit to the use of this queuing system, banks could place in the queue all payments whose value they expect to be offset by incoming payments. Banks' real-time payments would equal the amount of net payment outflows that they would expect during the day—equivalent to the multilateral net debit of a net settlement system. If expectations were fully realized and banks held sufficient balances to fund their payments, the amount of balances held would equal the amount of settlement payments that the banks would need if they settled payments in a multilateral net settlement system. At the same time, banks would have the advantages of real-time release of payments and the associated release of payments from the queue throughout the day. This is the essential theoretical benefit of this design.

No practical implementation of this system is likely to achieve the theoretical maximum in liquidity savings. In fact, the practical implementation of this queuing system is an important aspect of the mechanism. One important element is that the receipt-reactive system relies on some funds flowing among participants to trigger the release of queued payment messages. If all banks were to queue all their payments, all payments would remain queued. In such a case, the system operator could consider using a "gridlock-resolution" mechanism to break the logjam and release some payments from the queue, as in Bech and Soramäki (2001, 2002).

Appendix B: Simulation Results and Analysis

To gauge the effects of some of the liquidity enhancements described in our article, we tested various features of these possible enhancements using a simulation program developed by the Bank of Finland. The simulation program is a version of the one described in Leinonen and Soramäki (1999) and Koponen and Soramäki (1998). (A more in-depth description can be found at the Bank of Finland's website: <http://www.bof.fi/sc/bof-pss>.) The simulations first generated baseline output data for both real-time gross settlement (RTGS) and net settlement systems. Further simulations examined an alternative enhancement that releases gross payments against the aggregate amount of incoming funds within each minute—receipt-reactive gross settlement (RRGS).

We randomly selected 20 percent, 50 percent, or 80 percent of all Fedwire Funds Service payments and placed those payments either into a queue for deferred settlement or into a netting system. Those payments not entered into the queue or netting system were settled by the RTGS system. With the exception of the changes in settlement time imposed by the queuing or netting arrangements, we assumed no behavioral changes in Fedwire that would affect the timing of payment entry. The bulk of our analysis was performed with ten days of data, directing 50 percent of payments to the deferred settlement mechanisms. The 20 percent and 80 percent simulations tested the network effect associated with varying degrees of participation in these queuing and netting arrangements. The 80 percent simulations were particularly time consuming, so the 20 percent and 80 percent sensitivity analyses were performed on only three days of data.

Because these simulations focus on reducing both the Federal Reserve's risk exposure in granting intraday credit and the liquidity use by banks, we selected statistics that assess these areas. The analysis involves average and peak overdrafts and settlement delays.

Data

The simulations were performed using ten typical days of funds transfer activity data from the Fedwire Funds Service (Table B1). The days were randomly selected from the period October 1999 through February 2000. We included all transaction types but eliminated payment transfers of less than $100. The transaction data only included master accounts. Subordinate account numbers were changed to their related master account numbers before simulation. A uniform random-number generator was used to select the 50 percent of payments to be queued in each treatment. The rest of the payments were automatically processed by the RTGS system according to their historical timing during the simulations. While not directly involved in the simulations, National Book-Entry System (NBES) securities transaction data were used for the overdraft analysis presented later.

Table B1
Summary Statistics for Fedwire Funds Data

Date	Number of Payments	Sum of Payments (Billions of Dollars)	Number of Banks	Average Value (Millions of Dollars)	Standard Deviation of Payment Value (Millions of Dollars)	Sum of Opening Balances (Billions of Dollars)
1/6/2000	369,094	1,181.34	6,289	3.20	28.66	10.03
1/26/2000	373,685	1,318.44	6,191	3.53	31.84	15.61
2/23/2000	406,644	1,421.39	6,339	3.50	31.47	16.90
2/24/2000	404,356	1,470.65	6,293	3.64	32.55	16.42
10/1/1999	541,075	1,840.46	6,767	3.40	32.85	21.50
10/8/1999	406,628	1,377.19	6,400	3.39	31.23	12.76
11/4/1999	373,811	1,329.56	6,228	3.56	32.23	15.38
11/10/1999	395,304	1,354.38	6,159	3.43	31.42	10.87
12/6/1999	400,689	1,394.28	6,234	3.48	30.95	10.88
12/16/1999	413,024	1,383.84	6,295	3.35	30.53	12.71

Source: Authors' calculations, based on data from Federal Reserve Bank of New York, Fedwire Funds Service.

Analytical Framework

In the following discussion, let s_{ij}^{t} represent a settlement of a payment order at time *t* from *i* to *j*. The balance at the end of any minute, *m*, is equal to the previous balance plus the difference between the cumulative value of outgoing and incoming payments: $i = 1, 2, \ldots, D$.

$$\text{(B1)} \quad b_i^m = b_i^{m-1} - \sum_{(m-1)<t\le m} \sum_{j\ne i} (s_{ij}^t) + \sum_{(m-1)<t\le m} \sum_{j\ne i} (s_{ji}^t),$$

where $m = 1, 2, \ldots, M$.

Overdrafts

Overdraft calculations are based on end-of-minute balances. For overdraft accounting purposes, a bank's balance is affected by several services. We attempt to extract the Fedwire Funds Service's contribution to the bank's balance, and hence its overdraft, from the bank's other non-Fedwire funds transactions using a method that mimics the Federal Reserve's overdraft accounting procedures.[7] This involves a comparison of the Fedwire funds and NBES balances to determine the applicable balance, b_i^m, applied in the following formulas. The analysis assumes that same-day NBES and non-Fedwire funds activities remain unchanged (see Appendix C for further elaboration). Government-sponsored enterprises, the Clearing House Interbank Payments System, Federal Reserve System banks, and government agency accounts were included in the simulations, but removed prior to analysis.

The overdraft during the day for any minute, *m*, and bank, *i*, equals the absolute value of a negative balance or zero.

$$\text{(B2)} \quad OD_i^m = \left| min(0, b_i^m) \right|.$$

The average continuous overdraft is

$$\text{(B3)} \quad Average\ OD = \frac{\sum_m \sum_i OD_i^m}{1{,}081},$$

that is, the sum of overdrafts for each bank during the day divided by the number of minutes Fedwire is open (eighteen hours and one minute).[8]

Peak overdraft is

$$\text{(B4)} \quad Peak\ OD = \max_m \left(0, \sum_i OD_i^m \right).$$

Delay and Time Statistics

The settlement delay for each payment is calculated as the time difference between payment origination by the sending bank and the final and irrevocable settlement of the payment. The two statistics that we use to measure the delay imposed by the queuing and netting arrangements in our proposed design are the delay statistic and the average time of settlement.

The delay statistic for the system is calculated as:

$$\text{(B5)} \quad Delay = \frac{\sum_t \sum_i \sum_{j, j\ne i} s_{ij}^{t,t'}(t - t')}{\sum_t \sum_i \sum_{j, j\ne i} s_{ij}^{t,t'}(T - t')}.$$

In the notation for the delay statistic, we capture, for each settled payment, both its entry time, denoted by *t*', and its release time, denoted by *t*. The delay statistic measures in the numerator the value of the settled payments multiplied by the time they spent delayed in the queue. In the denominator, the value of settled payments is multiplied by the time that payments could have been queued, had their settlement been delayed until the queue is closed.

The delay statistic is a standardized indicator that may take values between zero and one. In an RTGS system, for example, payments spend no time in the queue, and *t*'=*t*, resulting in a delay statistic equal to zero. In an end-of-day netting system, the settlement of payments is delayed until end of day, and *t*=*T*, resulting in a delay statistic equal to one.

The delay statistic places greater emphasis than the average time of settlement on the settlement of both early-morning and early-afternoon payments, as well as on smaller payments. Early-morning or early-afternoon payments carry more weight than their nominal value because the delay statistic repeatedly counts these payments for every minute that they remain unsettled.

The average time of settlement (ATOS) is the average time weighted by the value of the payments settled at each minute, *t*.

$$\text{(B6)} \quad ATOS = \frac{\sum_t \left(\sum_i \sum_{j\ne i} s_{ij}^t \right) \times t}{\sum_{i=0}^{T} \sum_i \sum_{j\ne i} s_{ij}^t}.$$

These statistics are calculated for all applicable treatments. In addition, we ran a statistical test on the average continuous overdraft statistic to provide added confirmation of a scenario's overdraft savings or loss. Because the same payment data are used for each simulation treatment, the statistics for each treatment can be viewed as different variables of the same group. Furthermore, the small, ten-day sample size and unequal variances across treatments suggest that a standard parametric statistical analysis is inappropriate. Therefore, we use the nonparametric Wilcoxon matched-pairs signed-rank test to determine whether a statistical difference in average continuous overdraft exists between the dependent groups or treatments. All treatments are compared with the baseline performance of the RTGS system. When a treatment shows a nominal increase or decrease in average continuous overdraft when compared with each of these two treatments, we conduct a one-sided test to determine whether a statistically significant increase or decrease can be found versus the null hypothesis that there is no statistical difference. All tests were conducted at the 5 percent level.

Treatments and Results

To properly compare aggregate statistics from the sensitivity analysis with the 50 percent simulations, we added two lines for the RTGS simulation results, as well as for all 50 percent simulations. The sensitivity analysis average and sensitivity analysis standard deviation figures represent aggregate statistics calculated using the three days in our 20 percent and 80 percent sensitivity analysis simulations: January 6, 2000; January 26, 2000; and November 4, 1999.

Real-Time Gross Settlement

The RTGS simulation provides a benchmark for the analysis of the alternative queuing and netting arrangements (Table B2). In this simulation, 100 percent of the payments are settled immediately by the RTGS system. The delay statistic for RTGS is zero by definition and the average time of settlement equals the time when an average dollar was submitted to the system.

One-Hour Net Settlement

Net settlement of queued payments occurred every hour, and the net amounts were settled immediately thereafter through the RTGS system (Table B3). Accounts had unlimited liquidity available. At 18:30, remaining queued transfers were netted and the net balances were transferred between banks.

Table B2
Real-Time Gross Settlement Simulations

Date	Average Overdraft (Billions of Dollars)	Peak Overdraft (Billions of Dollars)	Time of Peak Overdraft	Average Time of Settlement	Delay Statistic (Percent)
1/6/2000	19.87	65.54	15:31	14:28	0
1/26/2000	20.57	70.73	15:49	14:32	0
2/23/2000	19.51	68.60	15:54	14:31	0
2/24/2000	21.01	67.58	15:55	14:41	0
10/1/1999	20.22	67.58	14:23	14:39	0
10/8/1999	19.69	59.68	14:01	14:39	0
11/4/1999	21.14	69.20	14:38	14:37	0
11/10/1999	22.91	75.58	15:54	14:35	0
12/6/1999	19.67	59.10	15:47	14:43	0
12/16/1999	18.28	59.20	15:53	14:33	0
Average	**20.29**	**66.28**	**15:22**	**14:35**	**0**
Standard deviation	**1.23**	**5.47**	**0:44**	**0:04**	**0**
Average for three days	**20.52**	**68.49**	**15:19**	**14:32**	**0**
Standard deviation for three days	**0.64**	**2.67**	**0:36**	**0:04**	**0**

Source: Authors' calculations, based on data from Federal Reserve Bank of New York, Fedwire Funds Service.

Note: The figures for the average for three days and the standard deviation for three days are calculated for the days for which the sensitivity analysis simulations were conducted.

One-hour net settlement actually increases the average overdraft by 0.6 percent, although the difference is not statistically different from the RTGS overdraft. One-hour net settlement, like six-hour net settlement, lowers the peak overdraft slightly while generating a 7.5 percentage point addition in the delay indicator. As expected, the average time of settlement is delayed by twenty-one minutes when compared with the RTGS average time of settlement—a logical result of delaying 50 percent of the payments for up to an hour.

Six-Hour Net Settlement

Net settlement of queued payments occurred every six hours (6:30, 12:30, and 18:30), and the net amounts were settled immediately thereafter through the RTGS system (Table B4). Accounts had unlimited liquidity available. At 18:30, remaining queued transfers were netted and the net balances were transferred between banks. The average and standard deviation figures represent those statistics for the three days

Table B3

One-Hour Net Settlement Simulations with Alternate Levels of Participation

Date	Average Overdraft (Billions of Dollars)	Percentage Change from Real-Time Gross Settlement	Peak Overdraft (Billions of Dollars)	Percentage Change from Real-Time Gross Settlement	Time of Peak Overdraft	Average Time of Settlement	Delay Statistic (Percent)
20 percent							
1/6/2000	19.86	0.0	63.78	-2.7	15:31	14:33	2.49
1/26/2000	20.24	-1.6	70.62	-0.2	14:55	14:36	2.26
11/4/1999	21.01	-0.6	67.09	-3.0	14:38	14:43	2.82
Average	**20.37**	**-0.7**	**67.16**	**-1.9**	**15:01**	**14:37**	**2.52**
Standard deviation	**0.58**	**0.8**	**3.42**	**1.6**	**00:27**	**0:04**	**0.28**
50 percent							
1/6/2000	20.02	0.8	59.08	-9.9	15:31	14:43	7.24
1/26/2000	20.36	-1.0	68.94	-2.5	14:53	14:46	6.86
2/23/2000	19.48	-0.2	66.53	-3.0	15:54	14:46	7.03
2/24/2000	21.36	1.6	68.30	1.1	16:10	14:55	7.38
10/1/1999	20.27	0.2	64.18	-5.0	15:10	14:54	7.72
10/8/1999	19.96	1.4	59.80	0.2	14:01	14:54	7.72
11/4/1999	21.27	0.6	67.80	-2.0	15:23	14:52	7.84
11/10/1999	23.49	2.5	76.83	1.6	16:31	14:50	7.54
12/6/1999	19.65	-0.1	57.01	-3.5	16:07	14:58	8.00
12/16/1999	18.21	-0.4	58.43	-1.3	16:22	14:49	7.97
Average	**20.41**	**0.6**	**64.69**	**-2.4**	**15:36**	**14:51**	**7.53**
Standard deviation	**1.41**	**1.1**	**6.19**	**3.3**	**0:46**	**0:04**	**0.39**
Average for three days	**20.55**	**0.1**	**65.27**	**-4.7**	**15:15**	**14:47**	**7.31**
Standard deviation for three days	**0.64**	**1.0**	**5.39**	**4.4**	**0:20**	**0:04**	**0.49**
80 percent							
1/6/2000	19.06	-4.1	56.36	-14.0	15:31	14:49	9.94
1/26/2000	19.77	-3.9	69.67	-1.5	15:49	14:51	9.31
11/4/1999	20.66	-2.3	67.93	-1.8	15:31	14:59	10.55
Average	**19.83**	**-3.4**	**64.66**	**-5.6**	**15:37**	**14:53**	**9.93**
Standard deviation	**0.80**	**1.0**	**7.24**	**7.1**	**00:10**	**0:05**	**0.62**

Source: Authors' calculations, based on data from Federal Reserve Bank of New York, Fedwire Funds Service.

Note: The figures for the average for three days and the standard deviation for three days are calculated for the days for which the sensitivity analysis simulations were conducted.

involved in our 20 percent and 80 percent simulations: January 6, 2000; January 26, 2000; and November 4, 1999.

Six-hour net settlement produced a modest 3.2 percent reduction in average overdraft, although, once again, the difference is not statistically significant. However, this treatment produced the lowest overall peak overdraft. The 35 percent delay statistic is roughly five times that of one-hour net settlement and, as we will see, is nearly three times that of RRGS. The average time of settlement was one hour and thirteen minutes later than in RTGS.

Receipt-Reactive Gross Settlement

The gross amount of payments received during each minute provided the available liquidity for release from the queue (Table B5). The payments subject to deferral were held in the queue if they were not offset by incoming payments in that minute. The available liquidity from incoming payments resets to zero at the start of a new minute and does not accumulate past that minute. Payments settled on a first in, first out (FIFO) basis when a bank received sufficient incoming funds. Queued

TABLE B4
Six-Hour Net Settlement Simulations with Alternate Levels of Participation

Date	Average Overdraft (Billions of Dollars)	Percentage Change from Real-Time Gross Settlement	Peak Overdraft (Billions of Dollars)	Percentage Change from Real-Time Gross Settlement	Time of Peak Overdraft	Average Time of Settlement	Delay Statistic (Percent)
20 percent							
1/6/2000	20.53	3.4	63.55	-3.0	15:31	14:56	13.30
1/26/2000	19.63	-4.6	65.27	-7.7	14:55	15:01	14.04
11/4/1999	21.43	1.4	64.44	-6.9	14:38	15:07	14.59
Average	**20.53**	**0.0**	**64.42**	**-5.9**	**15:01**	**15:01**	**13.97**
Standard deviation	**0.90**	**4.1**	**0.86**	**2.5**	**00:27**	**0:05**	**0.65**
50 percent							
1/6/2000	20.47	3.0	69.99	6.8	15:39	15:42	34.56
1/26/2000	19.27	-6.3	60.67	-14.2	14:53	15:44	34.70
2/23/2000	19.58	0.4	65.72	-4.2	15:54	15:42	33.56
2/24/2000	18.83	-10.4	58.67	-13.2	16:45	15:48	33.64
10/1/1999	17.83	-11.8	59.59	-11.8	14:25	15:45	32.83
10/8/1999	20.14	2.3	56.63	-5.1	16:14	15:51	35.88
11/4/1999	19.88	-5.9	56.85	-17.8	16:36	15:49	35.41
11/10/1999	22.92	0.1	70.41	-6.9	16:31	15:45	34.00
12/6/1999	19.43	-1.2	55.01	-6.9	16:06	15:51	34.56
12/16/1999	16.19	-11.5	47.92	-19.1	15:53	15:44	34.38
Average	**19.45**	**-4.1**	**60.15**	**-9.3**	**15:53**	**15:46**	**34.35**
Standard deviation	**1.75**	**5.8**	**6.95**	**7.7**	**0:44**	**0:03**	**0.90**
Average for three days	**19.87**	**-3.2**	**62.50**	**-8.7**	**15:42**	**15:45**	**34.89**
Standard deviation for three days	**0.60**	**5.3**	**6.76**	**13.3**	**0:51**	**0:03**	**0.46**
80 percent							
1/6/2000	18.15	-8.7	51.37	-21.6	14:23	16:25	54.70
1/26/2000	16.20	-21.2	50.26	-28.9	15:57	16:29	55.94
11/4/1999	17.62	-16.6	50.67	-26.8	16:06	16:31	55.67
Average	**17.32**	**-15.6**	**50.77**	**-25.9**	**15:29**	**16:28**	**55.44**
Standard deviation	**1.01**	**6.4**	**0.56**	**3.8**	**00:57**	**0:03**	**0.65**

Source: Authors' calculations, based on data from Federal Reserve Bank of New York, Fedwire Funds Service.

Note: The figures for the average for three days and the standard deviation for three days are calculated for the days for which the sensitivity analysis simulations were conducted.

payment messages were transferred to RTGS for settlement. The nondeferred payments were settled immediately by the RTGS system and did not affect the incoming funds accounting. Starting at 17:30, the remaining queued payments were spread evenly over the next thirty minutes and settled by the RTGS system.

In sum, receipt-reactive gross settlement offers a significant overdraft reduction coupled with an increase in the peak overdraft. The RRGS produced statistically significant lower average continuous overdrafts than did the RTGS treatment.

Indicators of Liquidity Use

Overdraft calculations use only the negative balances and therefore measure only the lower end distribution of balances according to a cutoff point of zero. While this is useful from a risk management standpoint, we calculate further statistics regarding the performance of these systems by analyzing them in terms of their liquidity usage. Each simulation restructures the timing of the original RTGS payments by changing the release sequence of the payments. By doing so, the different

Table B5

Receipt-Reactive Gross Settlement Simulations with Alternate Levels of Participation

Date	Average Overdraft (Billions of Dollars)	Percentage Change from Real-Time Gross Settlement	Peak Overdraft (Billions of Dollars)	Percentage Change from Real-Time Gross Settlement	Time of Peak Overdraft	Average Time of Settlement	Delay Statistic (Percent)
20 percent							
1/6/2000	21.41	7.8	76.52	16.8	15:45	14:44	3.51
1/26/2000	20.20	-1.8	67.91	-4.0	14:55	14:46	3.01
11/4/1999	21.04	-0.5	69.98	1.1	15:24	14:55	3.53
Average	**20.88**	**1.7**	**71.47**	**4.4**	**15:21**	**14:48**	**3.35**
Standard deviation	**0.62**	**5.2**	**4.49**	**10.8**	**00:25**	**0:05**	**0.30**
50 percent							
1/6/2000	19.18	-3.4	78.12	19.2	16:52	15:19	15.61
1/26/2000	15.06	-26.8	60.52	-14.4	16:48	15:13	12.32
2/23/2000	15.90	-18.5	68.51	-0.1	16:38	15:15	13.38
2/24/2000	17.24	-18.0	70.92	4.9	16:53	15:18	12.81
10/1/1999	14.18	-29.9	64.44	-4.6	16:48	15:22	14.06
10/8/1999	19.05	-3.2	76.50	28.2	16:46	15:22	14.78
11/4/1999	17.89	-15.4	72.58	4.9	16:51	15:24	16.42
11/10/1999	21.97	-4.1	89.96	19.0	16:23	15:17	13.56
12/6/1999	20.82	5.8	78.78	33.3	16:50	15:18	11.03
12/16/1999	13.89	-24.0	66.23	11.9	16:55	15:14	13.42
Average	**17.52**	**-13.6**	**72.66**	**9.6**	**16:46**	**15:18**	**13.74**
Standard deviation	**2.77**	**11.9**	**8.55**	**14.9**	**0:09**	**0:03**	**1.58**
Average for three days	**17.38**	**-15.3**	**70.40**	**2.8**	**16:50**	**15:18**	**14.78**
Standard deviation for three days	**2.11**	**11.7**	**9.00**	**16.9**	**0:02**	**0:05**	**2.17**
80 percent							
1/6/2000	12.59	-36.7	67.76	3.4	17:12	16:29	19.02
1/26/2000	8.61	-58.1	45.93	-35.1	17:05	16:29	23.11
11/4/1999	13.28	-37.2	66.07	-4.5	17:02	16:29	25.35
Average	**11.49**	**-44.0**	**59.92**	**-12.5**	**17:06**	**16:29**	**22.50**
Standard deviation	**2.52**	**12.3**	**12.15**	**20.3**	**00:05**	**0:00**	**3.21**

Source: Authors' calculations, based on data from Federal Reserve Bank of New York, Fedwire Funds Service.

Note: The figures for the average for three days and the standard deviation for three days are calculated for the days for which the sensitivity analysis simulations were conducted.

systems generate different liquidity levels and balance distributions than the original RTGS system. When evaluating the different simulations' temporal restructuring of the original RTGS payments, the approaches presented here attempt to indicate efficiency of liquidity use both above and below zero, providing a better overall view of each simulation's effect on liquidity usage. We do this indirectly by measuring both the degree of difference in the simulation balances when compared with RTGS balances and the direction of that difference.

Our first liquidity calculation measures the average absolute change in balances that occurs per minute for each bank. In effect, this calculation gives the amount of money that an average bank would have to move, either in or out of its account, for any given minute of the day. A liquidity-usage measure calculates the extent to which the balance must fluctuate in order to settle the payments. An RTGS system requires the most liquidity.

To measure liquidity, we first calculated the absolute value of a bank's change in balance from one minute to the next and summed this amount across all banks for a given minute. We did this for all 1,080 difference periods, summed the results, and divided by $1{,}080 \times N$, with N being the number of banks. The b_i^m used in the liquidity equations is the sum of each bank's end-of-minute balance across the three days subject to the alternative levels of payment submission simulations.

Average funds transfer =

$$\frac{1}{1{,}080 \times N} \sum_{m=2}^{1{,}081} \sum_{i=1}^{N} \left| b_i^m - b_i^{m-1} \right| \quad \forall \, (b_i^m - b_i^{m-1}) < 0 \, .$$

Our second measure is the maximum funds transfer across the minutes:

Maximum funds transfer =

$$\max_m \left(\sum_{i=1}^{N} \left| b_i^m - b_i^{m-1} \right| \right) \quad \forall \, (b_i^m - b_i^{m-1}) < 0 \, .$$

Our third measure of liquidity use in the systems is an indirect one. We calculated the degree of difference in the balances by measuring the independence exhibited between the end-of-minute balances of RTGS and the simulated system. Our independence calculation produced Pearson correlation coefficients for each minute and summed them across the 1,081 minutes of the Fedwire day. We then divided by 1,081 to get the average per minute. For RTGS, the correlation of its end-of-minute balances with itself is one. For the simulated systems, this number is the correlation between end-of-minute balances in the simulated system and those in the RTGS system. Lower numbers demonstrate more independence from the original RTGS payment distribution. The $b_{i,SIM}^m$ and $b_{i,RTGS}^m$, respectively, represent the collection of the pertinent simulated balances and the RTGS balances in minute *m*. The balances included in this collection are the sum of each bank's end-of-minute balance across the three days subject to the alternative levels of payment submission simulations.

$$\textit{Correlation with RTGS} = \frac{1}{1{,}081} \sum_{m=1}^{1{,}081} corr_m(b_{i,SIM}^m - b_{i,RTGS}^m) \, .$$

Our fourth measure, the skewness of the difference in balances, gauges the degree of positive change in balances imposed by the simulated system on the original RTGS payments. The difference in balances between the simulated system and RTGS is calculated for each bank and minute. A skewness statistic is generated for each minute and the average for the day is then calculated. The $b_{i,SIM}^m$ and $b_{i,RTGS}^m$, respectively, represent the sum of each bank's simulated and RTGS end-of-minute balances across the three days subject to the alternative levels of payment submission simulations.

$$\textit{Skewness} = \frac{1}{1{,}081} \sum_{m=1}^{1{,}081} skewness_m(b_{i,SIM}^m - b_{i,RTGS}^m) \, .$$

Appendix C: Funds Overdraft Accounting Procedure

An explanation of daylight overdrafts can be found in Coleman (2002). When determining a bank's balance, the Federal Reserve's Daylight Overdraft Reporting and Pricing System (DORPS) accounts for several funds credits and debits that we could not observe. These funds are not processed on the Fedwire Funds Service and are posted to the DORPS system through other means. We call these postings "extraneous funds" and include such funds primarily from checks, the Automated Clearing House network, return checks, currency and coins, savings bonds, and account deficiency credits and debits. Extraneous funds play a major role in a bank's balance management. To circumvent this problem, we had to employ the following method:

We had access to the following information: the DORPS total end-of-minute balances, National Book-Entry System (NBES) transaction data, and Fedwire funds data. Since the DORPS balance data contain the opening balance for Fedwire funds and the NBES has an opening balance of zero, end-of-minute balances were constructed from the transaction data. The following formulas describe the end-of-minute balance situation for each bank at a particular minute m:

(C1) $$Totalbal_m = NBESbal_m + FedwireFundsbal_m + XFundsbal_m .$$

The extraneous funds balance was extracted according to the following formula:

(C2) $$XFundsbal_m = Totalbal_m - NBESbal_m - FedwireFundsbal_m .$$

The RTGS extraneous funds and NBES balances were then held constant. The Bank of Finland simulator used the opening balance to create new Fedwire funds balances, $FedwireFundsbal_m^*$. The Fedwire funds balance was then constructed using the RTGS extraneous funds balance:

(C3) $$Fundsbal_m = NBESbal_m + Fundsbal_m^* .$$

The new funds balance, in conjunction with the RTGS book-entry securities balance, resulted in a new total balance:

(C4) $$Totalbal_m^* = NBESbal_m + Fundsbal_m .$$

We then compared the three components in equation C4 to determine each bank's applicable funds overdraft, $FundsOD_m$, according to the following DORPS accounting principles:

If $Fundsbal_m \geq 0$, then $FundsOD_m = 0$.

If $Fundsbal_m < 0$ and $NBESbal_m < 0$, then $FundsOD_m = Fundsbal_m$.

If $Fundsbal_m < 0$ and $NBESbal_m \geq 0$:

If $Totalbal_m^* \leq 0$, then $FundsOD_m = Totalbal_m^*$.

Otherwise, $FundsOD_m = 0$.

$FundsOD_m = OD_i^m$ in Appendix B for each bank i.

Endnotes

1. On average, overnight deposits made by commercial banks are worth about $15 billion.

2. See McAndrews and Trundle (2001) for a description of several new designs that have been put into use in various large payment systems and for a discussion of some specific policy issues that are associated with the novel designs.

3. We choose one calendar minute as our time period because banks' daylight overdrafts are calculated as of the end of each calendar minute. By choosing a one-minute period within which receipts can be set against the release of payments from the queue, we prevent the release of those payments from causing an overdraft at the end of the minute.

4. A single day's simulation for the receipt-reactive system with 80 percent of payments placed in the queue required more than two months to complete, using the single computer we employed for the simulations.

5. In such a case, a gridlock-resolution method of settling payments from queues might be useful. See Bech and Soramäki (2001) for a discussion.

6. These and other behavioral responses of queuing systems are discussed in McAndrews and Trundle (2001) and Roberds (1999).

7. These are activities unrelated to the daily Fedwire Funds Service and they are posted to the Daylight Overdraft Reporting and Pricing System at particular times. These include the Automated Clearing House network, checks, currency and coins, and savings bonds.

8. Effective May 16, 2004, the Federal Reserve Banks expanded the operating hours of the Fedwire Funds Service from eighteen hours to twenty-one-and-a-half hours. The new hours begin at 9:00 p.m. Eastern Time (ET) on the preceding calendar day (with a cycle date of the following calendar day) and end at 6:30 p.m. ET, regardless of the Bank's location or time zone.

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