Assessing Financial System Vulnerabilities: An Early Warning Approach

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- Regular surveillance of the financial system can provide market participants and policy-makers with early warning of emerging vulnerabilities, and can therefore inform decisions to take corrective actions that support financial stability and prevent losses in real economic activity.
- This article focuses on a quantitative method to identify vulnerabilities, specifically an imbalance indicator model and its application to Canada.
- The model proves useful for isolating historical imbalances that could be indicators of financial system vulnerabilities. It complements other sources of information, including market intelligence and regular monitoring of economic and financial data.

The Bank of Canada, and other central banks, regularly assesses vulnerabilities in the financial system. Such assessments can provide early indications to market participants and policy-makers of emerging areas of weakness in the financial system, and help to inform corrective actions that could be taken to support financial stability and prevent losses in real economic activity. The large costs associated with the 2007–09 global financial crisis illustrate the importance of improving this surveillance in order to reduce the likelihood and impact of future crises. Authorities worldwide are working toward this goal, as seen in the increased focus on this issue by the International Monetary Fund (IMF) and the Financial Stability Board.

Financial system vulnerabilities are conditions that make future financial system stress more likely. The degree of vulnerability may reflect, for example, the exposure of the financial system to particular risks. Imbalances create vulnerability by exposing the financial system to the risk of an abrupt correction and by reducing its ability to withstand other shocks.[1] Assessment of financial system vulnerabilities is a three-stage process: (i) detecting imbalances (vulnerability identification); (ii) estimating the likelihood of future financial system

1 The term "imbalances" refers to the conditions in a market or sector of the economy. For example, if house prices are overvalued or there is an oversupply of housing, one might say there is an imbalance in the housing market. The presence of an imbalance can be suggested by a variety of indicators associated with that market.

stress, given the imbalances; and (iii) estimating the impact of a potential stress episode on the financial system and the real economy, should it occur (impact assessment or stress testing).[2] This article focuses on vulnerability identification using an imbalance indicator model (IIM).[3]

IIMs are quantitative models that identify vulnerabilities in a financial system by comparing current economic and financial data with data from periods leading up to past episodes of financial stress. Using quantitative models to identify vulnerabilities has several advantages. These models add rigour to discussions on the evolution of imbalances by enabling more-precise comparisons with the past, thus allowing us to draw lessons from history. As well, indicators used in IIMs can provide earlier warnings of imbalances than surveys of market participants. In addition, the performance of quantitative models can be objectively measured based on actual results, helping policy-makers to improve their surveillance over time.[4] However, judgment is required in interpreting the results of these models, which need to be placed in the context of information from other complementary sources, including market intelligence gathered through discussions with participants and regular monitoring of economic and financial data.

◀ *Imbalance indicator models identify vulnerabilities in a financial system by comparing current economic and financial data with data from periods leading up to past episodes of financial stress*

The article begins by defining episodes of financial stress. It then describes the selection of countries, variables and thresholds for a typical IIM. The results of an IIM applied to Canada and several other advanced economies are presented. A few cautionary words on the mechanical interpretation of the results then follow, and the article ends with suggestions for future research into IIMs and their use for risk analysis.

Defining and Identifying Episodes of Financial Stress

Since the goal of vulnerability identification is to detect imbalances within a financial system that could signal future episodes of financial stress, it is necessary to define what is meant by a stress episode. Conceptually, a stress episode involves one or more of the following phenomena: increased uncertainty about the fundamental value of assets and the behaviour of investors, greater uncertainty about exposures of counterparties, and decreased willingness among market participants to hold risky and illiquid assets (Hakkio and Keeton 2009). Since none of these phenomena can be observed directly, financial stress must be inferred from the behaviour of asset prices and other financial variables. A severe episode of financial stress is considered a financial crisis—a systemic event that typically involves large losses in the banking or financial sector, a bailout of one or more financial institutions, activation of deposit guarantees, public injections of liquidity into financial markets, or a run on key financial markets or institutions. Financial crises are typically associated with large drops in economic activity. A period of elevated stress may not culminate in a financial crisis if the banking system is well capitalized or the policy response is adequate (as was the case in Canada during the 2007–09 global financial crisis). However, high financial stress is still associated with impaired financial market functioning and disrupted financial intermediation, and can result in a large contraction in the provision of credit and activity in the wider economy. Policy-makers therefore wish to avoid this stress by taking preventive measures to address vulnerabilities and increase the resilience of the financial system.

2 The Bank has developed two stress-testing models to assess the potential impact on balance sheets in the banking and household sectors of a plausible but severe macroeconomic scenario. Côté (2012) provides an overview of these models. For a description of the MacroFinancial Risk Assessment Framework (MFRAF), see Gauthier and Souissi (2012). The Household Risk Assessment Model (HRAM) is described in Faruqui, Liu and Roberts (2012).

3 IIMs are often referred to as "early warning" models.

4 For an in-depth discussion of the benefits of IIMs, see Bussière (2013).

Box 1

International Monetary Fund Financial Stress Index

The International Monetary Fund (IMF) financial stress index (FSI) includes measures of large shifts in asset prices, an abrupt increase in risk/uncertainty, and abrupt shifts in the liquidity and health of the banking system.[1] It has seven components: volatility of the real effective exchange rate; stock market volatility; stock market decline; corporate and interbank lending spreads (i.e., the difference between the interest rates on corporate or interbank loans and on government debt of comparable maturity); the banking sector "beta" (which is a measure of the volatility of bank shares and their correlation with equity markets in general); and the inverted term spread. In tranquil periods, all of these components would have low readings, leading to little indication of financial stress.

The IMF FSI is available for 17 advanced economies at a monthly frequency. It is highly correlated with other available FSIs and produces comparable forecasts of macroeconomic performance (Kliesen, Owyang and Vermann 2012). Since FSIs are typically high-frequency measures, they allow for precision in dating episodes and also provide a measure of the severity of an episode. One of their limitations, however, is that they do not account for differences in the importance of intermediated versus market-based credit across countries.

1 The data set is described in Balakrishnan et al. (2009) and Cardarelli, Elekdag and Lall (2009), and is available at http://www.imf.org/external/pubs/cat/longres.aspx?sk=23039.0.

In this article, we use two complementary methods to identify episodes of financial stress. The first method uses a continuous measure of financial conditions, a financial stress index (FSI) developed by the IMF (**Box 1**), to identify elevated FSI periods, defined as sustained periods in which the FSI recorded extreme values, i.e., the FSI exceeded the normal historical range for at least three consecutive months.[5] Periods that are less than a year apart are counted as a single episode. Using this approach, we identify 32 periods of elevated FSI in the 17 advanced countries for which the IMF FSI is available.[6] The second method is a narrative approach that uses information from the existing literature to determine the dates of financial crises. For example, this approach identifies two financial crises for the United States—the savings and loan crisis in the late 1980s and the financial crisis that began in 2007—and none for Canada.[7] For the remainder of the article, the term "stress episodes" refers to episodes identified using either method.

Combining results from the two approaches yields a total of 37 episodes of financial stress for the countries in our sample.[8] The dark and light grey bars in **Chart 1a** and **Chart 1b** show the stress episodes identified for Canada and the United States using the two methods. The recent financial crisis originated in the United States in the summer of 2007 and quickly spread to other advanced economies through financial linkages, resulting in a high level of stress observed for all countries in our sample during the 2007–09 period,

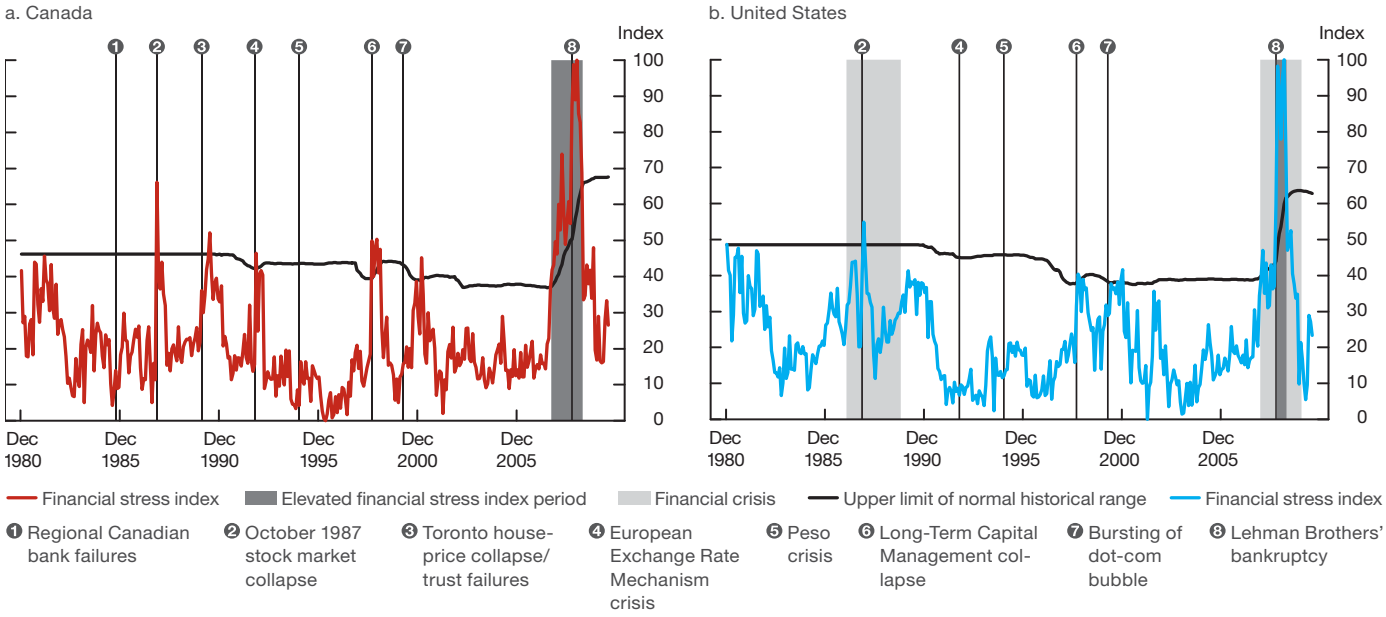
5 A country's readings exceed the normal historical range when they are higher than their 10-year rolling average by at least two standard deviations. The practical implication of taking rolling averages is that the upper limit of the normal range rises following large stress events and falls after a sustained period of relative calm. In our sample, this ensures that periods that would have been classified as stress episodes at the time that they occurred continue to be captured as stress episodes, even after the data from the 2007–09 global financial crisis are observed. Before the crisis, the threshold used is almost constant. An alternative way to set the upper limit on the normal range of the FSI is to use a historical benchmark, such as the level of the FSI observed during the Long-Term Capital Management collapse in 1998.

6 The countries in the sample are Austria, Australia, Belgium, Canada, Denmark, Finland, France, Germany, Italy, Japan, the Netherlands, Norway, Spain, Sweden, Switzerland, the United Kingdom and the United States.

7 The need to use the second (narrative) approach arises because the FSI is an imperfect measure of financial system stress. The elevated FSI periods do not cover all known financial crises.

8 There were 10 instances where financial crisis periods and elevated FSI periods overlapped, most of them during the 2007–09 global financial crisis. To avoid double counting, the overlapping periods were combined and counted as a single episode, starting at the earliest date provided by either method and ending at the latest date.

Chart 1: Stress episodes

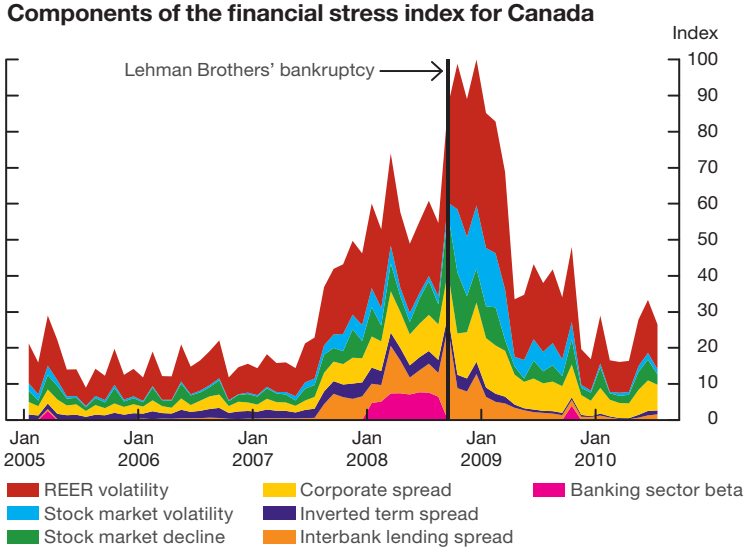


Note: The original index is centred at 0 and is rebased in the charts to lie between 0 and 100 for each country. As a result, the FSI values in the charts are not comparable across countries.

Sources: Bank of Canada and International Monetary Fund financial stress index

Last observation: July 2010

Chart 2: Components of the financial stress index for Canada



Notes: REER volatility is an index of time-varying volatility of monthly changes in the real effective exchange rate. Corporate spread is an index of the difference between corporate bond yields and long-term government bond yields. Inverted term spread is the difference between the government short-term rate and the government long-term rate. Interbank lending spread is an index of the difference between interbank rates and the yields on short-term government bonds. Banking sector beta is an index of the correlation between the total returns to the banking sector stock index and the overall stock market index.

Sources: Bank of Canada and International Monetary Fund financial stress index

Last observation: July 2010

particularly after the collapse of Lehman Brothers Holdings Inc. in September 2008. The rise in the FSI for Canada in mid-2007 reflects, in part, stresses in the non-bank asset-backed commercial paper market, which widened the spreads between the interbank interest rates and yields on government bonds, as well as corporate spreads (**Chart 2**).[9] Since the FSI-based method identifies

9 For a discussion of the events during this period, see Bank of Canada (2007).

episodes where the FSI is high for a sustained period, it does not include some relatively brief periods of high FSI, such as the collapse of Long-Term Capital Management (LTCM) in 1998 and the brief period of elevated FSI in 2001.[10]

Having identified the historical stress episodes, the next step is to determine the indicators that can help to predict these periods in advance.

Building an Imbalance Indicator Model

A key empirical challenge in building an IIM is the selection of countries to be included in the sample. Since the number of stress episodes experienced by any one country is typically small, using a broad sample of countries allows the use of others' experiences to identify the critical thresholds, as well as to test the validity of the model. Nevertheless, country-specific characteristics, such as the structure and regulation of financial markets, can differ widely across countries, potentially affecting the performance of indicators and thresholds. To increase comparability in economic and structural aspects, our model uses data on only advanced economies. The data are monthly and the model is estimated for 17 advanced economies over the period from December 1980 to December 2009.

A broad range of variables could be leading indicators of stress episodes, including those related to the financial, corporate, government, household and external sectors. To ensure that the exercise is relevant for informing preventive policy actions, we consider a variety of indicators for each sector that could be expected to signal a stress episode up to two years before the event. For example, the financial indicators used include the growth in return on equity for the banking sector and the ratio of overall private sector credit to GDP. To address the issue of limited comparability in the levels of variables, due to structural differences across countries, alternative transformations of the same data series, such as growth rates over different horizons and deviations from trends for every variable, are considered.

A broad range of variables could be leading indicators of stress episodes, including those related to the financial, corporate, government, household and external sectors

In our model, an indicator signals future stress when it rises above a threshold level that tends to be associated with historical stress episodes. Readings of an indicator above the threshold therefore suggest an imbalance. We consider several possible values of the threshold for each indicator and choose the one that simultaneously minimizes two errors: the error of failing to signal before stress occurs and the error of signalling an imbalance even when stress does not subsequently occur (see **Box 2** and Roberts (forthcoming) for further details on the methodology for selecting the thresholds).[11] This approach helps to identify the best threshold for each variable and to determine the most robust predictors of stress episodes (that is, those with the lowest error rates). Extracting signals from these indicators on a regular basis can highlight changes in existing imbalances and detect potential imbalances that merit more-intensive analysis or debate.[12]

Identifying Imbalances

The IIM is reasonably successful at identifying imbalances with considerable lead time. **Table 1** shows the signals given by a set of indicators before the recent financial crisis and other selected periods.[13] Data up to December 2009 are used to estimate the thresholds, and these estimated thresholds are then applied to data from recent (2010–11) and current (2012–2013Q2) periods.

10 One caveat here is that the FSI measures the outcomes and does not take into account policy responses. For example, the LTCM collapse is not identified as an elevated FSI period, because a quick policy response limited the duration and intensity of financial system stress.

11 See also Davis and Karim (2008) and Manasse and Roubini (2005).

12 This approach is typically referred to as the "signal extraction" approach.

13 Not all of these periods were followed by stress events as defined by our criteria.

Box 2

Estimating Thresholds for Indicators

An indicator signals a potential imbalance if it breaches its estimated threshold. A signal is considered "true" if a stress episode follows in the next 24 months and "false" if a stress episode does not follow in the next 24 months. For any given threshold, the performance of the indicator can be judged using the categories in **Table 2-A**:

Table 2-A: Assessment of true and false signals of stress episodes

	Stress occurs in next 24 months (pre-stress periods)	No stress occurs in next 24 months (normal periods)
Signal	A (number of true imbalance signals)	B (number of false imbalance signals)
No signal	C (number of false balance signals)	D (number of true balance signals)

"A" is the number of months in which the indicator issued an imbalance signal and a stress episode followed; "B" is the number of months in which the indicator issued an imbalance signal but a stress episode did not follow (Type I error); "C" is the number of months in which the indicator did not signal an imbalance but a stress episode followed nonetheless (Type II error); and "D" is the number of months in which the indicator did not issue an imbalance signal and none was called for (since a stress episode did not occur in the next 24 months).

A perfect indicator will have no observations in B and C, A will equal the total number of pre-stress months, and D the total number of normal months in the sample. To optimize the value of each indicator, its threshold is chosen at the point where the following "loss function" is minimized:

$$f(\overline{x}) = \frac{1}{A + B + C + D} * \left[\frac{CD}{C + D} + \frac{AB}{A + B}\right].$$

We then calculate the adjusted noise-to-signal ratio and use it to eliminate indicators that have no predictive power.[1]

1 The adjusted noise-to-signal ratio is computed as [B/(B + D)]/[A/(A + C)] or the proportion of false imbalance signals in normal periods (the noise) divided by the proportion of true imbalance signals among the pre-stress periods (Kaminsky, Lizondo and Reinhart 1998). A value greater than one indicates that the indicator performs worse than a coin flip.

The indicators cover four key areas of potential vulnerabilities: broad leverage, asset prices, the banking sector and the external sector. Within each category, indicators were selected based on their performance in signalling stress events, while also reflecting our judgment on the range of sectors in which financial stress would materialize. The indicators are shown for Canada as well as for the United States, the United Kingdom and Australia.

The second column in the table reports the threshold estimated for each indicator using cross-country data, and the third column indicates its accuracy, as measured by the adjusted noise-to-signal ratio (the lower, the better). The row for each indicator reports the percentage of quarters during the selected period that the indicator exceeded its estimated threshold.[14] The cells are shaded red if the variable exceeds the estimated threshold for at least three quarters during the selected period, and yellow if the indicator breaches the threshold for one or two quarters. The remainder of this section discusses the key results, and the next section focuses on how judgment can be applied to interpret the results.

Historical event 1: The 2000 dot-com crash

Throughout 1998 and 1999, the indicator for the growth of equity prices signalled an imbalance for all four countries. The dot-com crash occurred shortly afterward; however, since the FSI did not reach a sustained high level during this period, the dot-com crash is not considered an episode of financial stress according to our methodology. Many of the other indicators did not issue an imbalance signal. An explanation for why this event did not

14 We tested five alternative dependent-variable specifications. The broadest specification is described in the text and its results are reported in Table 1. The estimated thresholds are similar across the different specifications for most indicators.

Table 1: Indicators of financial system vulnerabilities

	Threshold	Noise-to-signal ratio	Pre-dot-com crash 1998–99				Pre-financial crisis 2005Q3–07Q2				Recent period 2010–11				Current period 2012–13Q2			
			CA	US	UK	AU	CA	US	UK	AU	CA	US	UK	AU	CA	US	UK	AU
Broad leverage																		
Credit-to-GDP gap (percentage points)	4.7	0.50						100%	100%	88%	88%		38%	13%	67%			
Ratio of household debt to GDP (per cent)	70.9	0.43			13%		50%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Deviation of ratio of household debt to GDP from 10-year moving average (per cent)	10.9	0.52				100%	100%	100%	100%	100%	100%		25%	75%	100%			
Asset prices																		
Equity prices, 3-year real growth (per cent per year)	7.5	0.62	88%	100%	100%	63%	100%	100%	100%	100%	13%				17%	33%	17%	
House prices, 5-year real growth (per cent per year)	6.9	0.45					75%	75%	100%	63%								
House-price gap	12.6	0.27					63%	100%	100%		13%			25%				
Ratio of house prices to income (index, long-term average = 100)	110.5	0.18					38%	88%	100%	100%	100%		100%	100%	100%		100%	100%
Banking sector																		
Deviation of return on equity for banks from 10-year moving average (per cent)	17.1	0.47	38%		50%		63%	50%	100%	63%								
External sector																		
Current account deficit (per cent of GDP)	4.8	0.22				63%		100%		100%				13%				
Deviation of real effective exchange rate (REER) from 10-year moving average (per cent)	20.2	0.12			13%		100%			100%	75%			100%				100%

Legend

	Indicator does not exceed threshold (no signal).	CA = Canada
X%	Indicator exceeds threshold for one or two quarters in the time frame (weak signal).	US = United States
X%	Indicator exceeds threshold for three or more quarters in the time frame (strong signal).	UK = United Kingdom
		AU = Australia

Notes: The thresholds for each variable are calculated using pooled data for 17 countries from December 1980 to December 2009. A grid search identifies thresholds by minimizing a loss function that measures the classification error of signals. The blank cell indicates missing data. The house-price gap is the deviation of the house-price index (January 2010 = 100) from its trend, as measured by the Hodrick-Prescott filter. Growth rates are calculated as: *Growth Rate = 100 * [(Value$_t$ /Value$_{t-h}$) ^ (12/h) - 1]*, where *h* is the number of months.

have a more widespread impact is suggested by the credit-to-GDP gap,[15] which serves as an approximate measure of excessive leverage across the private sector. This indicator did not signal an imbalance at that time.

Historical event 2: Global financial crisis

In the two years leading up to the 2007–09 global financial crisis, a variety of measures signalled the presence of imbalances in all four countries. Based on the estimated threshold of 4.7 per cent, the credit-to-GDP gap signalled that there was an imbalance in credit conditions—a credit boom—in three of the countries—the United States, the United Kingdom and Australia—before the financial crisis. The indicators that signalled imbalances for both Australia and Canada during the 2005Q3–07Q2 period should not be interpreted as suggesting that these imbalances caused the recent period of financial stress, which was triggered by factors external to these countries. For Canada, the signals in 2005Q3–07Q2 suggest that signs of the imbalances in the housing sector began to emerge during that period. The average annual growth of real house prices over the previous five years was above the estimated threshold of 6.9 per cent per year for six of the eight quarters in 2005Q3–07Q2.

15 The credit-to-GDP gap is the deviation of the ratio of aggregate private sector credit to GDP from its trend.

In summary, the results in **Table 1** suggest that the IIM is reasonably successful in isolating imbalances in key sectors. Before the global financial crisis, several indicators consistently signalled stress for at least two years before the event. In addition, for the entire sample, there were nearly as many signals one to two years before a stress episode as there were within one year of the episode. These results indicate that the signals of imbalances are persistent and that policy-makers could have warnings more than a year before a stress episode.[16] Our results are broadly consistent with results in the literature on IIMs, which has found excessive leverage and elevated asset prices to be key leading indicators of financial system vulnerabilities in advanced economies.[17]

◀ *Results indicate that policy-makers could have warnings more than a year before a stress episode*

Recent imbalances in Canada

During more recent periods, from 2010 to 2011 and from 2012 to the second quarter of 2013, the credit-to-GDP gap signalled elevated private sector debt in Canada in 11 out of 14 quarters. For the housing sector, the indicators appear to give varying signals. The ratio of house prices to income has been above the estimated threshold levels since the fourth quarter of 2006, but the house-price gap exceeded the threshold in only one quarter during 2010 and 2011 (while remaining elevated—ranging from 7 per cent to 15 per cent—until the second quarter of 2012). The average annual growth rate of real house prices over the previous five years was below the estimated threshold in 2010 and 2011 (although it remained elevated—ranging from 3.7 per cent to 6 per cent—until the second quarter of 2011). The variation among different indicators highlights the need to apply judgment in interpreting the signals. The growth in house prices eased before the other two variables, which are slower moving and reflect a buildup of imbalances resulting from a prolonged period of moderately high growth in house prices at the national level. As of the second quarter of 2013, the growth in house prices suggested a further easing of the housing market imbalances (with the growth rate falling to 2.9 per cent), although, as expected, the ratio of house prices to income suggested that the imbalance persisted. Also of note, there are no warning signals from indicators of banking sector health and external imbalances during this period.

Interpreting the Results

There are several areas where judgment needs to be applied when drawing conclusions about the financial system vulnerabilities identified by the IIM.

First, as noted in the previous section for Canada, indicators in the same sector can give different signals. An additional example is seen in the results for other countries, where, in the current period (2012–13Q2), the two measures of leverage (the credit-to-GDP gap and ratio of household debt to GDP) provide quite different signals for the United States, the United Kingdom and Australia. One reason for these different signals from related indicators is a basic distinction in the implicit views they embody regarding long-run trends. Some variables are measured in levels (for example, the ratio of nominal house prices to income) and others as deviations from a trend (for example, the house-price gap). After a long period of growth in house prices, the measured trend in house prices will rise, causing the house-price gap to diminish. This would give a false sense of security in a long-lived

16 The results are robust to ending the sample at the fourth quarter of 2006, rather than December 2009. The predicted thresholds are similar to those from the baseline specification and thus the indicators are able to predict the 2007–09 financial crisis out of sample.

17 Babecký et al. (2013); Barrell et al. (2010); Borio and Drehmann (2010); Frankel and Saravelos (2010).

housing bubble (in which the measured trend does not reflect an increase in prices based on fundamentals). On the other hand, the ratio of house prices to income will overstate the extent of the true imbalances if part of the growth in house prices reflects fundamentals. Policy-makers therefore need to apply judgment when interpreting signals and assessing the degree of the imbalance in a sector.

Second, the indicators by themselves do not contain information about the triggers of any given crisis. For example, as noted earlier, the signals for the 2005Q3–07Q2 period in Canada cannot be interpreted as the causal factor in the development of the crisis itself, which largely originated in the United States and was transmitted to Canada.

Finally, these models are statistical and reduced-form in nature, which means that they will not be able to fully account for the impact of changes in economic structure or in the financial system (either through innovation or regulation).

For these reasons, the indicator signals should not be interpreted mechanically. Rather, information about underlying trends in these and other indicators as well as policy-makers' judgment are crucial to translating signals into an assessment of vulnerabilities. While monitoring several variables presented here, the Bank of Canada's *Financial System Review* takes a broader range of information into account in its overall assessment of risks.

Information about underlying trends in indicators as well as policy-makers' judgment are crucial to translating signals into an assessment of vulnerabilities

Conclusion

The analysis in this article has focused on identifying potential imbalances that could predict episodes of financial stress. By providing quantitative assessments, imbalance indicator models can instill more discipline and consistent analysis into the judgment of policy-makers. The model illustrated here provides useful and reasonable measures for isolating historical imbalances, thus providing the basis for assessing vulnerabilities in the financial system.

The model could be refined in several ways. First, it could be extended to take into account global factors in determining domestic vulnerabilities and data on additional sectors of the economy (e.g., sovereign risk). Second, the thresholds could be estimated separately for different types of stress events (e.g., a currency, housing or banking crisis). Third, policy-makers need to be able to summarize information from different indicators to get a sense of the overall level of risk. This could be done by combining the different indicators into a composite indicator, by using a multivariate model to estimate thresholds simultaneously for several indicators, or by using probability models that use information from all variables to predict the overall probability of a crisis (Christensen and Li 2013). Research on these topics is ongoing at the Bank.

Literature Cited

Babecký, J., T. Havránek, J. Matějů, M. Rusnák, K. Šmídková and B. Vašíček. 2013. "Leading Indicators of Crisis Incidence: Evidence from Developed Countries." *Journal of International Money and Finance* 35: 1–19.

Balakrishnan, R., S. Danninger, S. Elekdag and I. Tytell. 2009. "The Transmission of Financial Stress from Advanced to Emerging Economies." International Monetary Fund Working Paper No. WP/09/133.

Bank of Canada. 2007. *Financial System Review* (December).

Barrell, R., E. P. Davis, D. Karim and I. Liadze. 2010. "Bank Regulation, Property Prices and Early Warning Systems for Banking Crises in OECD Countries." *Journal of Banking & Finance* 34 (9): 2255–64.

Borio, C. and M. Drehmann. 2010. "Toward an Operational Framework for Financial Stability: 'Fuzzy' Measurement and Its Consequences." In *Financial Stability, Monetary Policy, and Central Banking*, edited by R. Alfaro, 63–123. Vol. 15 of *Central Banking, Analysis and Economic Policies*. Santiago: Central Bank of Chile.

Bussière, M. 2013. "In Defense of Early Warning Signals." Banque de France Working Paper No. 420.

Cardarelli, R., S. Elekdag and S. Lall. 2009. "Financial Stress, Downturns, and Recoveries." International Monetary Fund Working Paper No. WP/09/100.

Christensen, I. and F. Li. 2013. "A Semiparametric Early Warning Model of Financial Stress Events." Bank of Canada Working Paper No. 2013–13.

Côté, A. 2012. "Modelling Risks to the Financial System." Speech to the Canadian Association for Business Economics, Kingston, Ontario, 21 August.

Davis, E. P. and D. Karim. 2008. "Comparing Early Warning Systems for Banking Crises." *Journal of Financial Stability* 4 (2): 89–120.

Faruqui, U., X. Liu and T. Roberts. 2012. "An Improved Framework for Assessing the Risks Arising from Elevated Household Debt." Bank of Canada *Financial System Review* (June): 51–57.

Frankel, J. A. and G. Saravelos. 2010. "Are Leading Indicators of Financial Crises Useful for Assessing Country Vulnerability? Evidence from the 2008–09 Global Crisis." National Bureau of Economic Research Working Paper No. 16047.

Gauthier, C. and M. Souissi. 2012. "Understanding Systemic Risk in the Banking Sector: A MacroFinancial Risk Assessment Framework." *Bank of Canada Review* (Spring): 29–38.

Hakkio, C. S. and W. R. Keeton. 2009. "Financial Stress: What Is It, How Can It Be Measured, and Why Does It Matter?" Federal Reserve Bank of Kansas City *Economic Review* (2nd Quarter): 5–50.

Kaminsky, G., S. Lizondo and C. M. Reinhart. 1998. "Leading Indicators of Currency Crises." International Monetary Fund *Staff Papers* 45 (1).

Kliesen, K., M. Owyang and E. K. Vermann. 2012. "Disentangling Diverse Measures: A Survey of Financial Stress Indexes." Federal Reserve Bank of St. Louis *Review* (September/October): 369–98.

Manasse, P. and N. Roubini. 2005. "'Rules of Thumb' for Sovereign Debt Crises." International Monetary Fund Working Paper No. WP/05/42.

Roberts, T. "An Early Warning Model for Financial Vulnerability Assessment." Bank of Canada Discussion Paper (forthcoming).