



*Cruise
Performance
Monitoring*

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AIRLINES USE
CRUISE PERFORMANCE
MONITORING
TO DECREASE
OPERATING COSTS.

Cruise Performance Monitoring

In addition to what might be considered its more common use of determining flight planning and FMC performance factors, cruise performance monitoring can help airlines identify and solve in-service performance problems. Often, performance monitoring will identify a need for Boeing to assist in determining the solution to a given in-service problem. However, with a good understanding of the monitoring process and the interactions among the variables involved, airlines can do a significant amount of their own problem diagnosing and solving.

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Cruise performance monitoring has been used for many years by airlines that strive to operate their airplanes as efficiently as possible. These airlines know that continuous cruise performance monitoring of airplanes in their fleets can decrease operating costs relative to airlines that do not monitor airplane performance levels. Continuous cruise performance monitoring can give airlines the information they need to:

- Adjust the baseline performance levels they use for flight planning and flight management computer (FMC) fuel-required predictions so that the correct amount of fuel is loaded on each and every flight.
- Identify normal deterioration for a fleet of airplanes.
- Match the airplanes that perform best to their longest routes.

- Identify high fuel burning airplanes for possible maintenance.
- Validate performance degradation for extended twin-engine operations (ETOPS) critical fuel reserves planning (in lieu of the regulatory requirement of 5 percent fuel mileage deterioration allowance).
- Increase flight crew confidence in flight plans and possibly decrease the amount of discretionary fuel requested and loaded.

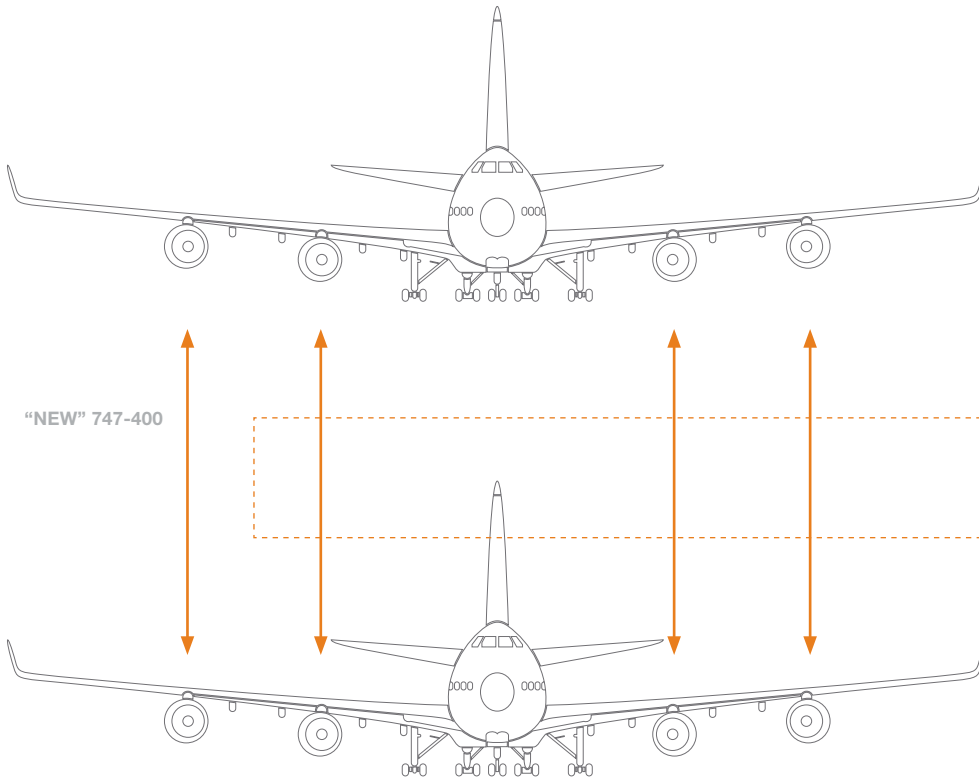
An additional, less recognized benefit of cruise performance monitoring is diagnosing and solving various airplane performance problems or issues. These case studies show how cruise performance monitoring was used to determine solutions to three different problems.

CASE STUDY I:

Airframe versus engine – causes of fuel mileage deterioration

An airline that operates a 747-400 airplane fleet was concerned about what it considered to be excessive fuel mileage deterioration relative to the fuel mileage levels its airplanes exhibited when they were new. The airline requested help from both Boeing and the engine manufacturer in determining what was causing this deterioration — the airframe, the engine, or both. Through a better understanding of the contributions that airframe and engine deterioration make to the overall fuel mileage deterioration, the airline could more efficiently focus its maintenance resources.

To help resolve this issue, the airline proposed an experiment involving an engine exchange



TOTAL FUEL MILEAGE DIFFERENCE

0.85%

FROM OLD TO NEW AIRPLANE USING THE OLD AND NEW ENGINES

between an old and a new airplane. A six-year-old 747-400, which was operating about 4.1 percent below the flight planning database level of fuel mileage, represented the old airplane, while a soon-to-be-delivered 747-400 represented the new one. The airline requested assistance and support from Boeing and the engine manufacturer in carrying out the experiment, which would:

- Measure pre-exchange fuel mileage on both the new and the old airplane (pre-engine swap).
- Swap all four engines between the new and old airplane.
- Measure fuel mileage again on both the new and the old airplane (post-engine swap).

By using the same physical set of four engines on two different airframes, the airline, Boeing, and the engine manufacturer agreed that any measurable difference in fuel mileage for the same set of engines on two different airframes could be attributed to airframe effects alone — that is, drag deterioration.

Boeing’s position was that proper maintenance of the exterior of an airplane would lead to minimal amounts of drag deterioration as an airplane ages. As a result, the experiment began by putting the old airplane through a complete D-check, including a configuration inspection, so that it would be considered as having a properly maintained

exterior before the engine swap. Control surfaces were riggered, seals were repaired, and one engine was replaced. A minor leak in the pneumatic system, discovered during the D-check, was not fixed by the airline (determined to cause about a 0.1 percent penalty in fuel mileage). Fuel mileage data was collected before and after the D-check to determine any change across the check, especially to quantify any changes resulting from riggering the flight control surfaces and replacing any worn seals. Fuel mileage improved 0.7 percent after the D-check, with 0.3 percent attributed to proper riggering of the flight controls and 0.4 percent attributed to the changing of one engine.

Fuel mileage data was then collected on both the old and new airplanes before and after the engine swap. The data collected was a combination of in-service data collected by the airplane condition monitoring system (ACMS) and hand-recorded data that was collected under more controlled test conditions.

Average results from all four sets of data were then compared to determine the differences in fuel mileage between the old and new airplanes with the same set of engines.

For both the old and new engines, the average improvement in fuel mileage for the new airframe relative to the old airframe was about 0.85 percent. The initial conclusion could be that the older

The experiment began by putting the old airplane through a complete D-check, including a configuration inspection.

airframe must contribute about 0.85 percent toward the overall fuel mileage deterioration originally observed on the old airplane and engine combination. However, about 0.3 percent of that difference is explainable. Of the total calculated difference of 0.85 percent, the pneumatic duct leakage discovered on the old airplane during the D-check contributed about 0.1 percent. In addition, the old airplane did not have the same revised vertical fin fairing as the new 747-400. If the older airplane had had the newer vertical fin fairing, it is estimated that the fuel mileage would have improved about 0.2 percent.

After adjusting for the pneumatic system leak and the newer vertical fin fairing, for the same set of engines the old airplane’s fuel mileage averaged about 0.5 percent worse than the new airplane.

The results are supportive of the position that the drag deterioration of a well-maintained airplane most likely will not exceed more than about 0.5 percent.

Case Study 1:
To help determine the primary cause of the fuel mileage deterioration, Boeing and the airline collected fuel mileage data on both a new and old 747-400 before and after an engine exchange.

NEW VERTICAL
FIN FAIRING

PNEUMATIC
LEAKAGE

ACTUAL UNEXPLAINABLE
DIFFERENCE

– 0.2%

– 0.1%

= 0.55%

CASE STUDY 2:

Investigation of a cruise fuel mileage shortfall

An airline expressed concern to Boeing that its new 737-800/CFM56-7B airplanes equipped with Aviation Partners Boeing (APB) blended winglets were exhibiting fuel mileage performance more than 2 percent worse than the Boeing database level, while its older, nonwinglet 737-800s (all approximately two years old) displayed fuel mileage performance similar to the database level. The airline, which collects cruise fuel mileage data on an ongoing basis, based its analysis on ACMS-collected cruise fuel mileage data analyzed using the Boeing Airplane Performance Monitoring (APM) program.

In initial discussions between Boeing and the airline, it was explained that the database being used by the airline to represent the 737-800 with blended winglets was based on the original winglet flight test results completed in early 2000. This is the same database used in the Flight Crew Operations Manual, the FMC, and the operational flight planning database. Additional flight tests had led to Boeing's latest, best assessment of the delivered performance of the winglets, which showed slightly less improvement than the original testing. This revised database, based on several additional flight test programs conducted in 2000 and 2001, includes a

different winglet drag increment (relative to a nonwinglet 737-800) and an aeroelastic correction absent in the earlier database.

At Mach 0.79, the difference between the two databases varies from 0.2 percent to 2.3 percent, depending on the exact conditions flown, with the airline's database predicting a better fuel mileage increment because of the winglets in all cases.

Upon request, the airline provided Boeing with ACMS data for two of its 737-800 airplanes with

Boeing's analysis of the data using the revised database concluded that two of the airplanes appeared to display fuel mileage performance about 3 percent below the latest Boeing-assessed winglet level – even more than the 2 percent originally suggested by the airline.

blended winglets. Boeing analyzed the data for each airplane using both the operational database and the revised database.

While the data was, on average, about 0.5 percent closer to the newer database level than the operational database level, Boeing's analysis did not agree with the airline's analysis.

Boeing's analysis of the data using the revised database concluded that two of the airplanes appeared to display fuel mileage performance about 3 percent below the latest Boeing-assessed winglet level — even more than the 2 percent originally suggested by the airline.

Further discussions with the airline revealed that it had been using passenger weight allowances of 70 kg per passenger, including carry-on baggage, and 13 kg per checked bag for all of its flights. As of June 1, 2002, the airline changed to the higher passenger weight allowances recommended in the Joint Aviation Requirements – Operations (JAR-OPS) 1. Checked baggage would be weighed whenever possible; otherwise, JAR-OPS 1 checked baggage weight allowances would be used. The average passenger weight allowances are significantly higher than the 70 kg per passenger the airline had been using. Because the data sent to Boeing for the two winglet-equipped airplanes was collected prior to June 2002, it was based on the lighter weight allowance of 70 kg per

passenger. The airline's analysis was based on data using a combination of the weight allowances.

As the investigation continued, the airline sent additional data to Boeing for the same two winglet-equipped airplanes — but only for conditions recorded after June 1, 2002, based on the higher JAR-OPS weight allowances. The airline also included data for one more winglet-equipped airplane, as well as for three nonwinglet airplanes. The data for the two winglet-equipped airplanes showed an immediate fuel mileage improvement of about 2.4 percent for each airplane, based on analyzing only the data from JAR-OPS weight allowances collected after June 1, 2002. This result led quickly to the belief that the previous 70 kg per passenger weight allowance was too light.

Although both the fuel mileage and thrust required changed significantly between data based on 70 kg per passenger and data based on JAR-OPS passenger weight allowances, the thrust-specific fuel consumption (TSFC) hardly changed. Errors in the estimated weight of an airplane present themselves as high or low drag but do not affect the fuel flow (i.e., TSFC) deviations calculated by APM.

Although a significant improvement was observed for both of the winglet-equipped airplanes originally analyzed with data recorded before June 1, 2002, the results for all six airplanes were still not as good as what Boeing experience indicated for this model. Further investigation determined that this airline operates its fleet of 737-800s in a mix of both scheduled and holiday charter flights, using the specific JAR-OPS weight allowances called out for each. The data sent to Boeing for the six airplanes included a mixture of data from both these types of flights. The average passenger weight allowance recommended for scheduled service is 84 kg per passenger and 76 kg per passenger for charter service (both are higher than the 70 kg per passenger originally used by the airline). At Boeing's request, the airline separated all of the post June 1, 2002, data into two groups: charter service and scheduled service. The data for each group was reanalyzed separately (see figs. 1 and 2).

The analysis revealed a significant discrepancy in demonstrated fuel mileage and thrust-required levels between the charter and scheduled flights. If airplane weight is underestimated, perceived airplane performance will be poorer than expected. Weight that is unaccounted for shows up as increased airplane drag and decreased fuel mileage. In this analysis, the TSFC deviations remained consistent between both sets of data, but the thrust-required (drag) deviations increased significantly for the charter flights — a strong indication of unaccounted-for airplane weight.

These results supported the conclusion that, for this airline, the JAR-OPS passenger weight allowances for scheduled flights more accurately reflect the true weight of the passengers plus carry-on baggage.

In this situation, Boeing proposed that the JAR-OPS passenger weight allowances as recommended for holiday charter flights were underestimating the airplane weight for this particular airline's charter operations. Although the airline was receptive to the possibility that the JAR-OPS passenger weight allowances might be too light for its holiday charter flights, it was not fully convinced. The airline believed that the JAR-OPS weight allowances for scheduled flights could just as easily be incorrect, in which case their airplanes were performing as poorly as the charter flight data indicated.

To determine which weight allowances were correct, the airline and Boeing agreed to collect delivery flight performance data on the airline's next new airplane delivery, a 737-800 with production blended winglets installed.

The advantages of collecting delivery flight data as opposed to in-service data are:

- The performance level of the airplane could be established at delivery.
- The airplane would be weighed at the Boeing factory with all the weight changes following weighing but preceding delivery accurately tracked and published in the Weight and Balance Manual. Therefore, the delivery flight empty weight could be considered accurate.
- Delivery flights are flown with minimum crew, so the issue of passenger weight allowances would not exist.

After collecting cruise performance data on the delivery flight, the airline would continue with its standard in-service data collection on both scheduled and charter flights. Comparing the results from the delivery flight with the results obtained in-service would help determine which JAR-OPS passenger weight allowances gave the airline more accurate airplane gross weights. If the weight allowances were too heavy (the airplane was actually lighter than estimated), then the in-service performance would appear to be better than the delivery flight performance. If the weight allowances

were too light (the airplane was heavier than estimated), then the in-service performance would appear to be worse than the delivery flight level.

The airline provided Boeing with the first 10 weeks of ACMS in-service data for the airplane following delivery, separating the data for charter flights and scheduled-service flights. For this analysis, the data was analyzed relative to the most recent 737-800 with winglets database. Although the delivery flight results showed the airplane to be slightly better than the demonstrated database level, the early in-service charter flight results show the airplane with an average perceived fuel mileage 3.3 percent worse than the demonstrated level (see fig. 3). Unaccounted-for weight shows up as airplane drag (thrust required). According to the charter flight data, the airplane experienced a 4.4 percent increase in thrust required on entering service, partially offset by a 0.7 percent drop in engine TSFC, for a 3.6 percent drop in fuel mileage from the delivery flight level. When the same airplane's scheduled service data for the same time period was analyzed, the fuel mileage was much closer to the delivery flight level. Average in-service fuel mileage for the first 10 weeks of operation deviated from the delivery level by only 0.8 percent (only 0.5 percent below the demonstrated level), which is within the ACMS's ability to determine fuel mileage over a given time period.

These results supported the conclusion that, for this airline, the JAR-OPS passenger weight allowances for scheduled flights more accurately reflect the true weight of the passengers plus carry-on baggage than the weight allowances recommended for the charter flights.

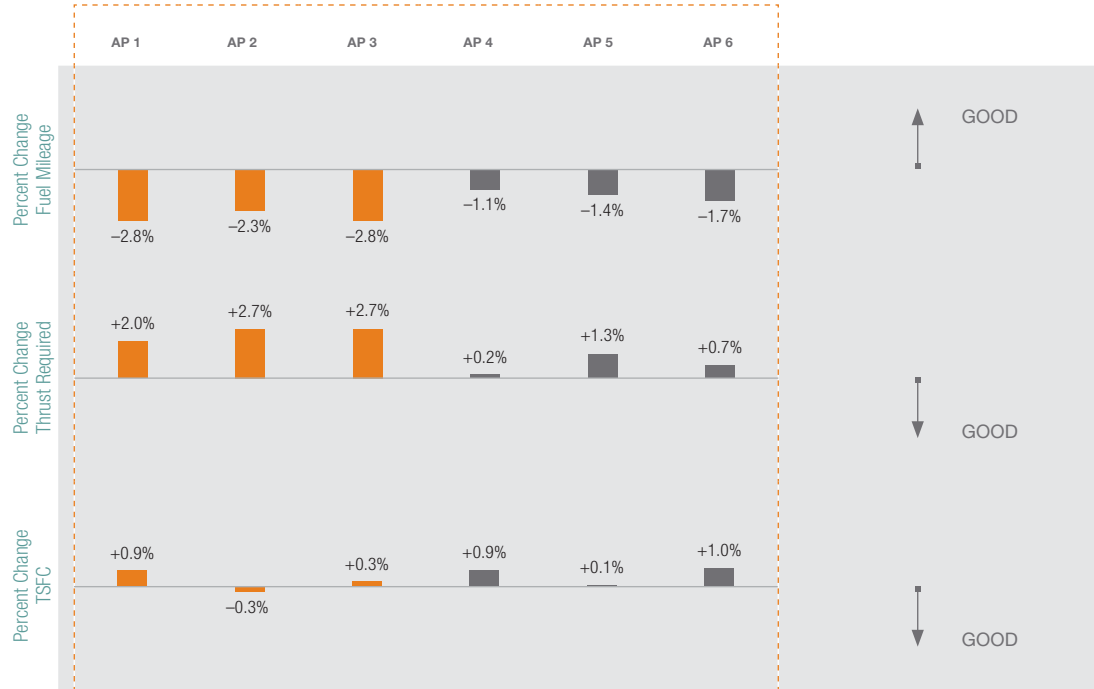
In addition, both are much more representative than the original 70 kg per passenger the airline had been using. The weight allowances for scheduled flights of 84 kg per passenger produce a more accurate zero fuel weight buildup and a truer representation of the actual performance of the airplane, with or without winglets.

The results of this case study identified a fleetwide airplane weight buildup issue for this particular airline. Boeing suggested that the JAR-OPS holiday charter passenger weight allowances appeared to be too light for this airline's operations, with unaccounted-for weight showing up as excess airplane thrust required (drag). Using the JAR-OPS-recommended passenger weight allowances for scheduled flights, the fuel mileage performance for its 737-800s — with and without winglets — is close to predicted and reflects Boeing expectations based on numerous flight tests and delivery flight results.

CHARTER SERVICE DATA ONLY
JAR-OPS 1 PASSENGER WEIGHT
ALLOWANCES

Figure 1

- = Airplane with APB winglets relative to winglet database
- = Nonwinglet relative to nonwinglet database



SCHEDULED SERVICE DATA ONLY
JAR-OPS 1 PASSENGER WEIGHT
ALLOWANCES

Figure 2

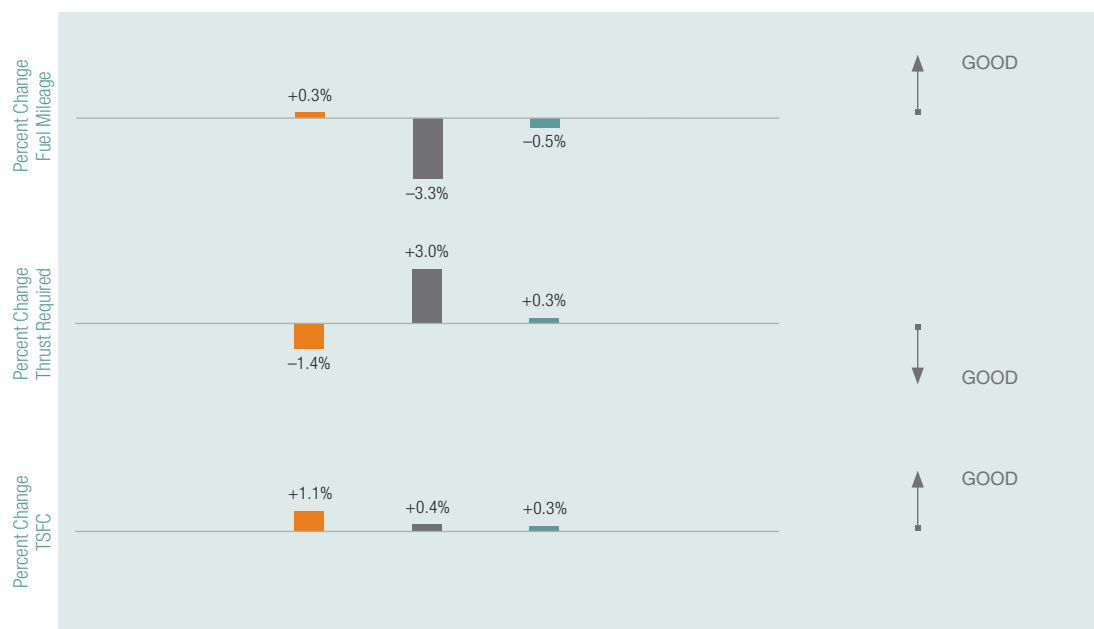
- = Airplane with APB winglets relative to winglet database
- = Nonwinglet relative to nonwinglet database



PERFORMANCE SUMMARY
DELIVERY FLIGHT VERSUS
IN-SERVICE (ALL DEVIATIONS
ARE RELATIVE TO THE
WINGLET DATABASE)

Figure 3

- = Delivery flight
- = Post delivery charter service
- = Post delivery schedule service



CASE STUDY 3:
Performance improvement resulting from 737-800 winglet retrofit

An airline requested assistance from Boeing to determine the airplane cruise performance improvement resulting from the retrofit installation of blended winglets on 14 of its 737-800s. To determine the magnitude of this improvement, cruise fuel mileage data collected after the installation of the winglets would be compared to data collected before the installation. The airline provided ACMS-recorded data collected on each of the 14 airplanes, before and after the installation of the winglets, to Boeing for analysis and comment.

Retrofitting the winglets is a two-step process comprising a structural reinforcement of the wing followed by installation of the winglet. Eleven of the airplanes had the wing reinforcement completed many weeks before the winglets were installed, with the airplanes returning to service with the

reinforced wings. For these 11 airplanes, the nonwinglet data was based on this reinforced wing configuration. Three of the airplanes had the wing reinforced and winglet installed at the same time. For these three airplanes, the nonwinglet data was based on the production nonreinforced wing. The two sets of data were analyzed separately in order to identify any differences in the improvement based on differences in the baseline before the winglets were installed.

Boeing analyzed the data for all 14 airplanes using the same in-house software tools used to analyze Boeing flight-test data. These software tools are different from the APM software provided to airline customers, but the analysis produces basically the same results. The main difference is that the Boeing in-house software normalizes the data points to nominal weight to pressure ratios (W/δ) chosen by Boeing while the APM software does not.

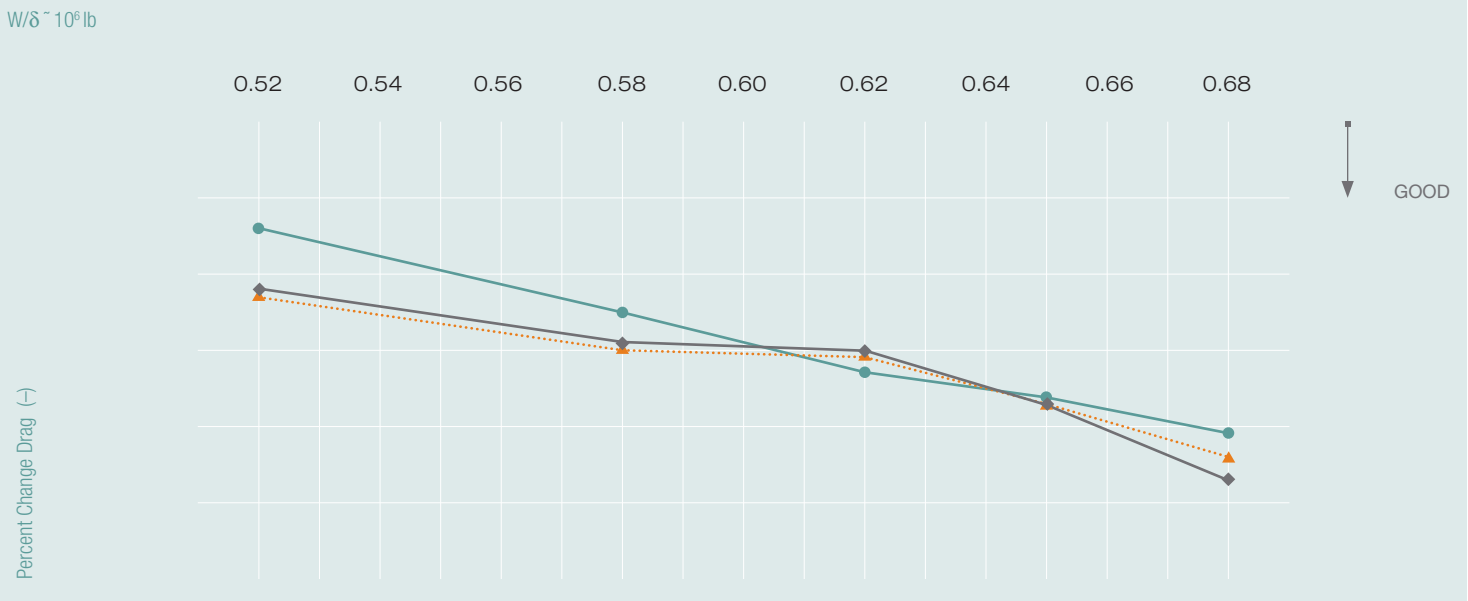
The improvements were plotted versus W/δ in order to illustrate that the magnitude of the

improvement depends on W/δ for a given Mach number. This dependency on W/δ is because the winglet improvement is a function of airplane lift coefficient, which in turn is a function of weight, altitude, and speed. The improvements were determined by comparing both the nonwinglet and winglet fuel mileage results to the nonwinglet 737-800 database. The performance improvement because of the winglet is not the average winglet deviation from the nonwinglet database; rather, it

Boeing's analysis of the data indicated a slight improvement in drag and fuel mileage (at a fixed weight) that resulted from the reinforcement of the wing structure.

DRAG IMPROVEMENT RESULTING FROM RETROFITTING 737-800 AIRPLANES WITH APB BLENDED WINGLETS

Figure 4



- ▲ = Winglet installation plus wing reinforcement relative to baseline wing
(based on in-service cruise fuel mileage measurements of three retrofit airplanes)
- = Winglet installation relative to reinforced wing
(based on in-service cruise fuel mileage measurements of eleven retrofit airplanes)
- ◆ = Predicted drag improvement
(based on Boeing flight-test results)

is the difference between the average deviations for the winglet and nonwinglet, both measured relative to the nonwinglet database. This same process was followed for each W/δ , and for the various sets of data (see figs. 4 and 5).

Boeing's analysis of the data indicated a slight improvement in drag and fuel mileage (at a fixed weight) that resulted from the reinforcement of the wing structure. The results indicated this improvement to be relatively small but still worth an average of a few tenths of a percentage at normal cruise weights and altitudes. Including the effects of both the wing strengthening and the addition of the winglets, the fuel mileage and drag improvements closely matched their predicted levels.

Because the improvement in drag is a function of W/δ for a given cruise speed, the actual improvement in fuel mileage that the airline would experience for any given flight conditions depends on the W/δ s flown during that airline's operations. The change in total fuel required to fly a given

route is determined by a combination of the improvement in fuel mileage offset by any increase in airplane weight. Retrofitting the winglets to the 737-800, including wing reinforcement, currently adds about 218 kg to the empty weight of the airplane, and this additional weight alone would increase fuel burn approximately 0.2 percent to 0.3 percent for an average 737-800 flight leg.

An analysis similar to the Boeing analysis could have been carried out by the airline itself using the spreadsheet output option from the APM software program. The results of analyzing the data in this manner would differ by only a relatively small amount from the analysis carried out using the Boeing in-house software. This same method of analysis could be used to investigate any type of modification to an airplane. Data collected before and after a modification would be compared to a reference database and the difference between the two sets of data would reflect the effect of the modification.

SUMMARY

The benefits of cruise performance monitoring are well known by many airlines that include the practice as part of their toolbox of practices aimed at efficient operation of their airplanes. The three case studies in this article illustrate the use of cruise performance monitoring to solve various cruise performance issues. Performance monitoring can also be used to identify flight planning and FMC performance factors and to monitor performance deterioration trends. Boeing has the resources to assist airlines with cruise performance monitoring analyses and to help them interpret results. For more information, contact David Anderson at david.j.anderson@boeing.com. **A**

FUEL MILEAGE IMPROVEMENT RESULTING FROM RETROFITTING 737-800 AIRPLANES WITH APB BLENDED WINGLETS

Figure 5

