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Evaluating the Operational Impact of Contactless Fingerprint Imagery on Matcher Performance

Shahram Orandi
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Shahram Orandi
John Libert
Bruce Bandini
Kenneth Ko
Craig Watson
Information Access Division
Information Technology Laboratory

John Grantham
Systems Plus, Inc.
Rockville, MD

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Table of Contents

List of Tables

List of Figures

Executive Summary

This study set out to examine the operational impact of introducing contactless fingerprint imagery on a state-of-industry high end commercial law enforcement grade matcher that was designed to operate on contact-collected fingerprint images in either a standard Ten-Print mode of operation, or a Mobile ID mode of operation. Of particular interest in this study were cases comprised of contactless fingerprint imagery for use as the biometric reference database. Also of interest was comparing and contrasting the performance of contactless fingerprint imagery on a Mobile ID matcher to that of a traditional Ten-Print matcher. It was hypothesized that while Ten-Print matchers are built to handle large volumes of contact images quickly and accurately, a Mobile ID matcher may have certain advantages in dealing with contactless fingerprint imagery as Mobile ID matchers are built to operate on images that may be cropped smaller than a full fingerprint impression, or operate on fewer images than a full set of ten fingerprints from both hands. Matching accuracy was measured in terms of false negative identification rate (FNIR). Due to the small experimental data set available, the experiment was not structured to measure false positive error rates.

Results showed that on a Ten-Print matcher using thresholds typical of operational casework (henceforth referred to as operational thresholds), the contact-to-contact control cases (6 of 72 total experimental treatments, Table 5) emerged as most accurate, with the FNIR ranging from 0 % to 0.5 % in these 6 cases. Of the remaining 66 cases, the D3 emerged as the highest performing contactless capture device in terms of accuracy (case #7 with D3 as probe, and case #8 with D3 as the biometric reference database, yielding an FNIR of 1.6 % at the lights-out threshold for these cases).

On a Mobile ID matcher configured at operational thresholds, accuracy measurements showed 19 of the 72 test cases tied as top performing cases (see Table 6) with an FNIR of 0 %. Of these 19 top performing cases, several contactless capture devices (D3, D4, D6, D7 and D8) were present in this top performing group.

A further examination of the Ten-Print and Mobile ID matchers was conducted at the same threshold (rather than operational thresholds for each), which showed almost five times as many test cases with an accuracy performance advantage on the Mobile ID matcher over the Ten-Print matcher (68 to 14, Figure 4). More importantly, with respect to accuracy, the best performing contactless capture device (D3) was measured at an FNIR of 0.8 % while the worst performing contact capture device was measured at an FNIR of 0.5 %. These results suggest that Mobile ID matchers may also provide a performance advantage when processing contactless fingerprint imagery, and may be key in establishing matcher performance parity between contactless and contact capture devices.

Examination of matcher throughputs (see Table 8) showed that cases that performed poorly on the Ten-Print matcher (mostly contactless cases) incurred a greater throughput penalty (7 417 milliseconds average) than cases that performed poorly on the Mobile ID matcher (2 267 milliseconds average penalty).

The key findings for this study are:

- Contactless fingerprint images from 200 volunteer participants were utilized on a modern fingerprint matcher designed for contact images, as the biometric reference database as well as probes.
- Contactless fingerprint images used in this study incurred penalties, in terms of both accuracy and throughput versus contact images, on both the Ten-Print and Mobile ID matchers.
- These penalties (accuracy, throughput) vary by the contactless fingerprint capture device.
- These penalties vary by matcher configuration (Ten-Print or Mobile ID caseloads).
- A matcher configured for Mobile ID caseloads may mitigate some of the penalty due to the matcher's inherent designed capability to operate on images with less area/information.

Abstract

This study set out to examine the operational impact of introducing contactless fingerprint imagery on a state-of-industry high end commercial law enforcement grade matcher that was designed to operate on contact-collected fingerprint images in either a standard Ten-Print mode of operation, or a Mobile ID mode of operation, depending on configuration. Contactless fingerprint imagery from six contactless capture devices was used, along with mated imagery from two contact-based capture devices using a block experimental design. Experimental cases were defined for the matching of contactless fingerprint imagery as either probe or biometric reference database, and matcher accuracy was measured in terms of false negative identification rate (FNIR). Due to the small data set available, the experiment was not structured to measure false positive error rates. Results showed that contactless fingerprint imagery can be used as the biometric reference database, but using these images will come at the price of matching accuracy on the Ten-Print matcher (FNIR of 0.5 % worst case for contact capture devices vs. FNIR of 1.6 % best case for contactless). The Mobile ID matcher seemed to close the gap between contactless and contact collected images with the best performing contactless capture device in terms of accuracy (D3) performing at an FNIR of 0.8 % while the worst performing contact capture device was measured at FNIR of 0.5 %. These results suggest that optimizations in place for the Mobile ID operation mode may also provide the matcher a performance advantage when processing contactless fingerprint imagery. Finally, the introduction of contactless fingerprint imagery did incur a larger throughput penalty on the Ten-Print matcher than it did on the Mobile ID optimized matcher.

Keywords

Contactless fingerprints; Touchless fingerprints; Biometrics; Accuracy; Throughput; Friction Ridge

Human Subjects Research

The National Institute of Standards and Technology Institutional Review Board reviewed and approved the protocol for this project and all subjects provided informed consent.

1. Introduction

In 2018, the National Institute of Standards and Technology (NIST)—in partnership and collaboration with the Federal Bureau of Investigation (FBI)—established several research tracks to examine contactless fingerprint capture, and its impact on interoperability as well as the operational impact on matching performance.

In NIST Interagency Report (NISTIR) 8307 "Interoperability Assessment 2019: Contactless-to-Contact Fingerprint Capture" [IR8307] a thorough examination of the fundamental aspects of contactless fingerprints was conducted, with a primary focus on the interoperability and fidelity of these images to legacy contact-based/contact collected images, with a biometric reference database (*henceforth may be referred to simply as database*) of legacy contact-based/contact collected images.

The study described in this report builds upon the foundation of NISTIR 8307, but focuses more on the *operational* impact of introducing contactless fingerprint imagery into a contact-collected matcher eco-system. This report also includes an independent study of contactless fingerprint imagery used both in the capacity of search images (probes) as well as background images (database), at operational thresholds as well as arbitrary thresholds. This study also includes an examination of the impact of contactless fingerprint imagery on the throughput of a matcher.

The study utilized a state-of-industry high end commercial law enforcement grade matcher, configured for both normal Ten-Print fingerprint identification caseloads, as well as Mobile ID caseloads. While the Ten-Print matcher is optimized to operate when a full set of rolled or flat fingerprint impressions are expected as input, the Mobile ID matcher is optimized to provide an enhanced capability to operate on fingerprints captured by personnel in the field using portable or mobile capture devices. These devices tend to collect fewer fingerprints than a full set that is traditionally captured in a fingerprint booking environment, and/or smaller fingerprint impressions than what are traditionally collected at a booking environment.

Although the Ten-Print matcher and the Mobile ID matcher have basic design commonalities, they can be quite distinct in terms of behavior.

2. Background

There are currently two prevalent modes of fingerprint capture employed in operations worldwide, flat fingerprint capture (where friction ridge detail is captured by pressing the finger friction ridge pad down onto the capture device and then lifted), and rolled fingerprint capture where the finger is first placed down on either the left or right edge and then rolled to the other edge on the capture device capturing more of its surface area in the rolling operation (see Figure 1).

There is evidence that increased friction ridge spatial coverage such as that provided by rolled fingerprint impressions can yield better performance in certain use cases over impressions that have less spatial coverage such as plain impressions [IR7112, IR7821]. The drawback to rolled fingerprint capture is that capturing each finger can take significantly longer time, can be more prone to sequence errors, and does not allow for capturing multiple fingers at the same time as do flat fingerprint captures.

Figure 1: Example of a Flat Fingerprint Impression (left) and Rolled Fingerprint Impression (right) of the Same Finger [SD302]

In 2004, the Fast Capture Initiative (FCI) was launched as a collaborative effort across multiple agencies within the U.S. Department of Justice to develop prototypes capable of collecting ten rolled-equivalent fingerprint impressions in 15 seconds or less. Between 2006 and 2008 the U.S. Government funded several prototypes which were produced between 2007 and 2009 of varying degrees of operational readiness, each with particular strengths. While the paramount goal of FCI was to capture rolled fingerprints quickly, the emergence of **contactless** fingerprint capture seemed to be a welcomed side-effect as it emerged in the various prototype devices.

Contact-based capture devices have certain intrinsic challenges that can be addressed by contactless capture devices. These include:

1. Making physical contact with the device allows for pathogen transfer between successive subjects who have made contact with that device.
2. Making physical contact with the device allows for contaminant transfer from the subject to the device capture platen resulting in potential degradation in device performance.
3. Making physical contact with the device (and correctly situating the hand for proper contact interaction) can be a time consuming and error prone process.

In an effort to further mature contactless technologies, in March of 2009, Department of Homeland Security Science and Technology Directorate (DHS S&T) awarded several grants to promote research and development of contactless fingerprint capture devices. The goal of such a system was the design basis for a whole new generation of biometric capture devices that could capture 10 fingerprints in less than 10 seconds without contact between the subject and the biometric sensor.

In addition to meeting the above goals, the devices were to also generate images that were of a certain forensic quality allowing them to be used effectively for both identification & verification purposes, as well as assure interoperability with legacy systems and devices. Currently in the United States such capture devices typically must meet the certification and standards put forth by the FBI through its Electronic Biometric Transmission Specification (EBTS) Appendix F [APF] process.

3. Study Objectives

The overall objective of this study is to examine the operational impact of introducing contactless fingerprint imagery on a state-of-industry high end commercial law enforcement grade matcher that was designed to operate on contact-collected images, with a comparative analysis of matcher behavior when configured for standard Ten-Print caseloads, as well as Mobile ID caseloads.

NIST's specific objectives for this study were:

1. Establish baseline of matcher performance:
   - Baseline performance in standard Ten-Print mode of operation (henceforth referred to as Ten-Print matcher)
   - Baseline performance when configured for Mobile ID mode of operation (henceforth referred to as Mobile ID matcher).

2. Measure matcher accuracy using a biometric reference database of mated contactless vs. contact collected probe images with a Ten-Print matcher configuration at operational thresholds.

3. Measure matcher accuracy using a biometric reference database of mated contactless vs. contact probe images with a Mobile ID matcher configuration at operational thresholds.

4. Compare accuracy differences between the Ten-Print matcher and Mobile ID matcher, using a biometric reference database of contact images vs. contactless probe images, at level-set arbitrary thresholds.

5. Measure throughput differences between the Ten-Print matcher and Mobile ID matcher, using a biometric reference database of contact images vs. contactless probe images, at level-set arbitrary thresholds.

6. Examination of Self-Matching (an image to itself) of contactless fingerprint imagery on Ten-Print and Mobile ID matchers.

4. Materials and Method

The study was conducted with a block design with each capture device/image type representing the various treatments being examined. The mated data (image pairs that are known to be a match, and captured from the same fingers of the same participant) utilized for this investigation consisted of fingerprints provided by 200 Federal employee volunteers that were invited to participate in May of 2019.

The mated data for the 200 volunteers comprised of approximately 1600 images (see 4.1 for caveats) and was augmented by approximately 3 million non-mated contact captured identities (or approximately 30 million images) to ensure the matcher contained an operationally realistic number of records in the biometric reference database. This biometric reference database was used for both the Ten-Print and the Mobile ID matchers.

4.1. Data Caveat: Thumbs

Contactless fingerprint capture presents unique challenges in capturing thumbs which are related to the anthropometrics of the human hand. While all contact capture devices were able to capture thumbs, some contactless capture devices were unable to capture thumb images in a timely manner given the limited resources of this study.

In consideration of these challenges, a decision was made by the investigating team to not include images of thumbs (fingers 1 and 6) in the testing and analysis for both the contact and contactless capture devices.

The term "Ten-Print" in context of referring to the matcher used in this study refers to the configuration of the matcher. All data submitted to the matcher contains 8 fingers or fewer given the specific test case.

4.2. Data Caveat: Small Subject Pool

Given the limited resources both in terms of time and available volunteer subject pool, the number of subjects collected was modest at n=200. This subject pool was further eroded by 7 due to collection challenges unrelated to the operation of the capture devices yielding n=193 subjects.

While this small n allows for a meaningful examination of false negative identification rates (see 4.7) between the various capture devices and matcher configurations, false positive error measurement granularity is limited to 0.5 % (1/193) at best. For a meaningful measurement of false positive error rates, the scale of data collection will need to be increased by at least an order of magnitude and the data partitioned so that an open-set evaluation of the matcher can be conducted.

To help maintain the fingerprint matcher at operationally realistic levels, the experimental biometric reference database was augmented by operational records (see 4.4)

4.3. Data Caveat: Collection Methodology

The data collection for this study was conducted in a controlled environment that facilitated the successful collection of the images. Collection of contactless images in real world settings may face challenges that were not encountered in this study.

4.4. Biometric Reference Database Selection

For each trial, the biometric reference database included up to 200 identities for a given test trial, plus

3 million additional non-mate records that are used in the NIST Fingerprint Vendor Technology Evaluation[1].

During each test scenario execution, only mates from one capture device of interest (either contactless or contact based) were enrolled in the biometric reference database to avoid multiple hits across the same identity for multiple capture devices.

4.5. Search Probe Generation

Images from the mated-pair collection were segmented, with the segmentation manually verified/corrected. No rotation correction was performed on the images.

The matcher used in this study is a state-of-industry high end commercial law enforcement grade matcher. The matcher supports both rolled fingerprints as well as flat fingerprint impression matching. The matcher also supports specific optimizations for data typical of Mobile ID.

This matcher does not however provide any explicit support for contactless fingerprint imagery. Its operational behavior vis-à-vis contactless fingerprint imagery is provided through the generation of legacy-compatible images by contactless capture devices, and is the focus of this study.

While it is possible that the matcher could be optimized to better address contactless fingerprint imagery, including possibly operating on contactless fingerprint imagery in a more native format, this was not the focus of this study.

[1] https://www.nist.gov/publications/fingerprint-vendor-technology-evaluation

4.6. Test Cases

The study encompassed eight capture devices of interest:

D1 – An optical (Frustrated Total Internal Reflection (FTIR)) **contact**-based Appendix-F-certified capture device.
D2 – An electroluminescent (EL) **contact**-based Appendix-F-certified capture devices.
D3 – A tabletop **contactless** capture device.
D4 – A tabletop **contactless** capture device.
D5 – A mobile (phone) **contactless** capture device.
D6 – A mobile (phone) **contactless** capture device.
D7 – A mobile (phone) **contactless** capture device.
D8 – A mobile (phone) **contactless** capture device.

Note that subjects processed on D1 were captured twice, **Encounter 1** (E1) and **Encounter 2** (E2).

Tests were run on the matcher configured for the Mobile ID optimized mode of operation (Mobile ID), as well as the Ten-Print optimized mode of operation (Ten-Print).

The combinations of all test trials above yielded 162 tests that were executed on the matchers and are summarized in Table 1.

Table 1: Summary of Test Cases Generated.

Matcher Configuration	Biometric Reference Database		Probe	
	Device	Fingers	Device	Fingers
Mobile ID	D1-E1		D1-E1	
	D1-E2		D1-E2	
	D2		D2	
	D3		D3	
	D4	8	D4	8
	D5		D5	
	D6		D6	
	D7		D7	
	D8		D8	
Ten-Print	D1-E1		D1-E1	
	D1-E2		D1-E2	
	D2		D2	
	D3		D3	
	D4	8	D4	8
	D5		D5	
	D6		D6	
	D7		D7	
	D8		D8	

4.7. Scoring Methodology

This study was conducted as a closed-set identification task where each identity (comprising of a set of fingers, defined henceforth as the *probe*) being searched for has an enrolled mate in the biometric reference database. The reason this study was conducted as a closed-set identification task due to the small sample size of the contactless data that was collected (200 subjects), therefore all available subjects were used in both the biometric reference database and probe set generation.

Expected matches at Rank-1 yield the measure of hit rate [IJCB] and candidates not returned, or returned with a score below the similarity score threshold constitute the miss-rate. False Negative Identification

Rate (FNIR) at candidate list Rank-1, or FNIR(1), or FNIR in the context of this study is the complement of the Rank-1 hit rate [IJCB]. Given N enrolled subjects, with L candidates in the candidate list returned by the matcher using a threshold of T and rank of R (in this paper, R is always equal to 1, and L is always equal to 220 per the configuration of the matcher in both Ten-Print and Mobile ID optimized modes of operation), FNIR is defined as:

$$FNIR\,(N,R,T,L) = \frac{\substack{Number\ of\ mate\ candidate\ searches\ where \\ candidate's\ mate\ is\ below\ threshold\ T\ or\ below\ rank\ R}}{Number\ of\ mate\ candidate\ lists, S_M}$$

As mentioned in section 4.2, this study utilized a very limited number of candidates in its test pool (n=200). While this small n allows for observation of FNIR behavior, the modest data available for this study did not allow for observation of false positive errors.

4.8. Score Thresholds of Interest

The biometric matcher used for this study is designed to support multiple decisional thresholds. These thresholds are designed to classify results of searches into categories that dictate a “lights-out” search (i.e., success or failure without further human intervention), as well as biometric candidates that warrant further adjudication by additional processing steps including a human examiner review (not a “lights-out” match). Furthermore, the system supports separate threshold settings for the Mobile ID and Ten-Print matcher.

For the purpose of this study, matching performance was measured according to the performance thresholds listed below in Table 2.

Table 2: Scoring Threshold Values Typical in Operational Configuration

Mobile ID	Ten-Print	Threshold Name	Notes
3 000	**8 500**	Low Confidence Hit	A candidate with a score below the low confidence threshold is considered a non-match, also referred to as a **“Green”** non-hit (●). A candidate with a score at or above the low confidence threshold, but below the high confidence threshold, is considered a *possible* match, also referred to as a **“Yellow”** hit (●). Candidates with a Yellow hit will require additional adjudication steps and manual review.
4 100	**15 000**	High Confidence Hit	A candidate with a score at or above a high confidence threshold is considered a “lights-out” biometric candidate with no further adjudication or review necessary as part of the initial biometric search process. This is also referred to as a **“Red”** hit (●).

In addition to the operational thresholds listed in Table 2, there are certain cases associated with test objectives where the Mobile ID and Ten-Print matchers needed to be compared at a level-set threshold to measure other aspects of matcher behavior. For this, the thresholds of **5 000** and **12 000** were selected completely arbitrarily with no analysis made of their fairness or fitness of use. These values were selected for cases where a level set comparison of the two matcher configurations was needed at the same exact threshold value.

4.9. Throughput Calculation Methodology

When test probes were submitted into the matcher, the amount of time that each took to yield a response was recorded in a log file. Matcher throughput was calculated as the average response time for each probe submitted to the matcher.

The following caveats and conditions apply to the throughput portion of this study:

- Matcher timing data was returned at a reported resolution of 1 milliseconds (ms) and inclusive of all processing overhead for each probe searched for.
- Matcher timing data analysis does not include the characterization (i.e., vectorization) phase of setting up the experiment, biometric reference database loading and enrollment times. Timing data returned was for each probe searched for after the matcher reached an operationally responsive state.
- No attempt was made to measure or remove underlying I/O overhead resulting from normal matcher operation.

- The computational environment used for this study was isolated physically and logically from the general computing environment at NIST.
- No general processes were executed on the machines involved in this study while the throughput test was being conducted.
- Matcher initialization and initial start-up times were not factored in measuring matcher performance. The test was commenced with the matcher fully initialized and at idle.

5. Results

The matcher's biometric reference database was initialized according to each test case being examined as described in section 4.6, and probe sets for that given test case were injected into the matcher for searching.

The resulting candidate lists for each test case were captured and scored according to the methodology described in section 4.7 yielding FNIR measurements for thresholds of interest (see Table 2). Additional descriptive statistical data including boxplots for the candidate scores obtained as a result of the various test cases has been provided in Appendix B.

The data presented in this section for each objective has been provided in a way to allow for quick visual comparison of matcher behavior under various scenarios. For additional finer-grained information, [numerical] performance data is also provided for selected scenarios.

The visualizations presented are optimized to provide large volumes of information in a relatively small space. Test cases are summarized in the following format:

(Device Number Populating Database) ◀ (Probe Device Number)

or

(Device Number Populating Database) ◁ (Probe Device Number)

The symbol "◀" denotes control cases where both probe and biometric reference database contain ONLY contact captured images.

The symbol "◁" denotes all other cases (can be a mix of contactless vs contact, or contactless vs contactless)

5.1. Objective 1: Baseline (Contact Database to Contact Probes) Accuracy on Ten-Print and Mobile ID Matchers at Operational Thresholds.

Biometric Reference Database Composition[2]:	**D1, both encounters, 8 fingers, full size**
Probe Set Composition:	D1, both encounters, 8 fingers, full size
Matching Threshold:	As defined in section 4.8 for Ten-Print caseloads.
Special Notes:	Represents baseline/control case
Number of test trials in this Objective:	4 for Ten-Print, and 4 for Mobile ID

The first objective of this study set out to establish how the matcher performs at a baseline level.

For this objective, only images from the two encounters with optical/FTIR Appendix F certified Device 1 (D1) were utilized.

To ensure the matcher behavior adheres to the symmetric property, each encounter was tested as the biometric reference database and the probe alternately. Self matches (i.e., Device 1 Encounter 1 to itself) were also conducted; these are examined separately in section 5.6.

This establishes baseline matcher performance and will be inclusive of any bias that may be present in the data selected for this study.

The thresholds used for this objective are analogous to the thresholds used in Ten-Print and Mobile ID configurations respectively.

5.1.1. Data for Objective 1

Table 3: Baseline Ten-Print Matcher Performance

Database	**Probe**	**FNIR (%)**		**Average Search Time, ms**
		T=8 500	T=15 000	
D1-E1	D1-E2	0.5	0.5	36 105
D1-E2	D1-E1	0.5	0.5	30 600

Table 4: Baseline Mobile ID Matcher Performance

Database	**Probe**	**FNIR (%)**		**Average Search Time, ms**
		T=3 000	T=4 100	
D1-E1	D1-E2	0	0	37 506
D1-E2	D1-E1	0	0	31 754

2 The NIST Test Bed also contained 3 million records in addition to the test case being examined. The composition of the test bed biometric reference database is described in section 4.4.

5.1.2. Findings for Objective 1

When configured for **Ten-Print mode** of operation, the matcher achieved an FNIR of 0.5 % at the low confidence threshold (yellow) and 0.5 % at the high confidence/lights-out threshold (red) set in this study (see Table 3).

When configured for **Mobile ID mode** of operation, the matcher achieved an FNIR of 0.0 % at the low confidence threshold (yellow) and 0.0 % at the high confidence/lights-out threshold (red) set in this study (see Table 4).

For both test trials, a biometric reference database of D1-E1 (Device 1 Encounter 1) took longer on average to search rather than using D1-E2 (Device 1 Encounter 2) as the biometric reference database (approximately 15 % longer), measured on both the Mobile ID and Ten-Print matchers. It is hypothesized that this may be due to isolated sample quality issues and amplified by the small sample size.

5.2. Objective 2: Contactless-Database vs Contact-Probes on Ten-Print Matcher at Operational Thresholds.

Biometric Reference Database Composition:	**All 8 devices, two encounters for D1, 8 fingers, full size**
Probe Set Composition:	All 8 devices, two encounters for D1, 8 fingers, full size
Matching Threshold:	As defined in section 4.8 for Ten-Print caseloads.
Special Notes:	Also includes contact-to-contact cases for comparison
Number of test trials in this Objective:	P(9,2) = 72

This objective represents the "gold standard" for high volume/high demand operations where the matcher has been built and tuned for processing transactions that normally contain all fingers of both hands (as either rolled or flat impressions) captured with state-of-industry contact devices or methods (i.e., FTIR or ink), under controlled fingerprint capture conditions with no cropping. The matcher for this scenario is referred to as the Ten-Print matcher for the scope of this study.

The goal of this objective is to measure performance of a Ten-Print matcher, but with contactless fingerprint imagery populating the biometric reference database.

5.2.1. Findings for Objective 2

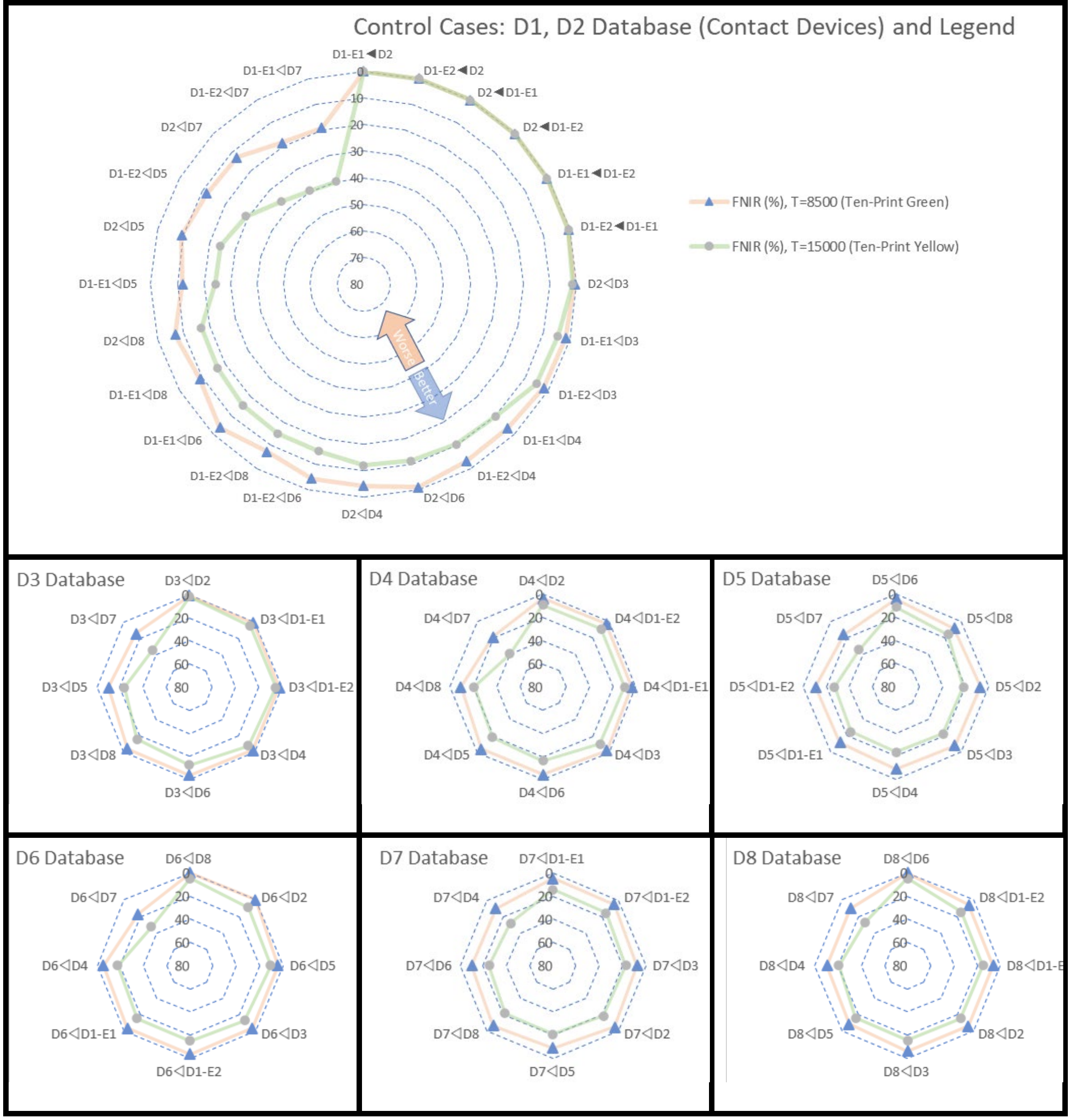
An examination of calculated accuracy data (see Figure 2 and Table 5) shows that at the high confidence threshold for Ten-Print (T=15 000) the contact-to-contact device control cases (cases #1 through #6) emerged as the best performing cases out of all 72 trials. FNIR was measured at 0 % for the first four cases, and increased to 0.5 % for cases 5 and 6 (D1-E1 vs D1-E2, and vice versa).

Test trial #8 represents the highest performing test trial where a contactless database (D3) was utilized for matching by an Appendix F certified device (D2), and yielded an FNIR of 1.6 % at the lights-out threshold.

While this error rate is small taken by itself, this jump in error for the contactless biometric reference database utilization represents a 320 % increase in FNIR versus the worst performing contact-to-contact case (FNIR of 0.5 % for contact biometric reference database vs contact probe, versus FNIR of 1.6 % for contactless database vs contact-probes).

5.2.2. Data for Objective 2

Figure 2: Comparative Accuracy of Contactless Database vs. Contactless Probes on Ten-Print Matcher at Operational Thresholds.



Legend:	D1: Contact, FTIR	D2: Contact, EL	D3: Contactless, Desktop	D4: Contactless Desktop	"◀": Contact Cases Only
	D5: Contactless Mobile Phone	D6: Contactless Mobile Phone	D7: Contactless Mobile Phone	D8: Contactless Mobile Phone	"◁": Contactless Cases

Table 5: Measured Accuracy Data For Objective 2

Trial #	Database ◁ Probe	FNIR (%), T=8500 (Ten-Print Green)	FNIR (%), T=15000 (Ten-Print Yellow)
1	D1-E1◀D2	0	0
2	D1-E2◀D2	0	0
3	D2◀D1-E1	0	0
4	D2◀D1-E2	0	0
5	D1-E1◀D1-E2	0.5	0.5
6	D1-E2◀D1-E1	0.5	0.5
7	D2◁D3	0.8	1.6
8	D3◁D2	0.8	1.6
9	D1-E1◁D3	1.5	4.6
10	D6◁D8	0	5
11	D8◁D6	0	5
12	D3◁D1-E1	1.5	5.2
13	D1-E2◁D3	2	5.2
14	D3◁D1-E2	2	5.2
15	D3◁D4	2.5	8.1
16	D6◁D2	0	9.1
17	D4◁D2	3.4	9.4
18	D4◁D1-E2	3.1	9.4
19	D4◁D1-E1	3.6	9.9
20	D1-E1◁D4	3.6	9.9
21	D4◁D3	2.5	10.2
22	D1-E2◁D4	3.1	10.4
23	D6◁D5	4.3	10.6
24	D5◁D6	4.3	11.2
25	D2◁D6	1	11.2
26	D2◁D4	4.2	11.9
27	D3◁D6	3.7	12.5
28	D6◁D3	3.7	13.1
29	D7◁D1-E1	4.6	14.5
30	D8◁D1-E2	5.7	14.6
31	D1-E2◁D6	4.4	15
32	D6◁D1-E2	3.7	15
33	D8◁D1-E1	6.2	15.1
34	D1-E2◁D8	7.3	15.1
35	D8◁D2	5.9	15.2
36	D8◁D3	6.1	15.3
37	D7◁D1-E2	5.2	15.6
38	D1-E1◁D6	3.7	15.7
39	D6◁D1-E1	3.7	15.7
40	D5◁D8	8.6	16.2
41	D8◁D5	8.6	16.2
42	D3◁D8	4.5	16.3
43	D4◁D6	4.4	16.4
44	D1-E1◁D8	8.9	16.7
45	D2◁D8	6.7	16.9
46	D7◁D3	7.6	17.2
47	D6◁D4	5.6	17.7
48	D4◁D5	4.5	18.2
49	D7◁D2	5	18.4
50	D8◁D4	10.7	20.5
51	D4◁D8	9.2	20.5
52	D7◁D5	9	20.7
53	D5◁D2	7.5	21.8
54	D7◁D8	7.1	21.9
55	D5◁D3	8.5	22.7
56	D3◁D5	10.1	23.7
57	D5◁D4	9.1	23.8
58	D1-E1◁D5	11.9	24.3
59	D2◁D5	9.2	24.3
60	D7◁D6	10	25.1
61	D5◁D1-E1	11.9	25.3
62	D5◁D1-E2	10.8	26.9
63	D8◁D7	10.2	28
64	D7◁D4	10.2	28.5
65	D1-E2◁D5	11.9	29
66	D6◁D7	16.9	32.7
67	D5◁D7	16.1	34.8
68	D3◁D7	14.7	35
69	D2◁D7	12.6	36.1
70	D1-E2◁D7	18.7	39.5
71	D4◁D7	19.3	39.7
72	D1-E1◁D7	19.2	40.1

Legend:	D1: Contact, FTIR	D2: Contact, EL	D3: Contactless, Desktop	D4: Contactless Desktop	"◀": Contact Cases Only
	D5: Contactless Mobile Phone	D6: Contactless Mobile Phone	D7: Contactless Mobile Phone	D8: Contactless Mobile Phone	"◁": Contactless Cases

5.3. Objective 3: Contactless-Database vs Contact-Probes on Mobile ID Matcher at Operational Thresholds.

Biometric Reference Database Composition:	**All 8 devices, two encounters for D1, 8 Fingers, full size**
Probe Set Composition:	All 8 devices, two encounters for D1, 8 Fingers, full size
Objective 3 Matching Thresholds:	As defined in section 4.8 for Mobile ID caseloads.
Special Notes:	Also includes contact-to-contact cases for comparison
Number of test trials in this Objective:	P(9,2) = 72

The introduction of the Mobile ID Best Practice Recommendation (BPR) [MOBID] into the ANSI/NIST standard [AN2K] opened the door for capture of fingerprint imagery using a new generation of portable capture devices designed to operate in the field rather than a central capture facility. The Mobile ID BPR allowed for smaller capture platens (spatial reduction of capture area) as well as the option to capture fewer than ten fingers for submission. Given this, manufacturers have had the opportunity to introduce optimizations to deal with reduced geometric capture surface and/or fewer fingers from the subject. The matcher for this scenario is referred to as the Mobile ID matcher for the scope of this study.

The goal of this objective is to see if a Mobile ID matcher performs better than a Ten-Print matcher, using the same experimental data with no specific changes to the data to favor either matcher configuration (no cropping of images or changes to number of available finger count from the original collection). The matcher for Objective 3 was configured for Mobile ID operational thresholds.

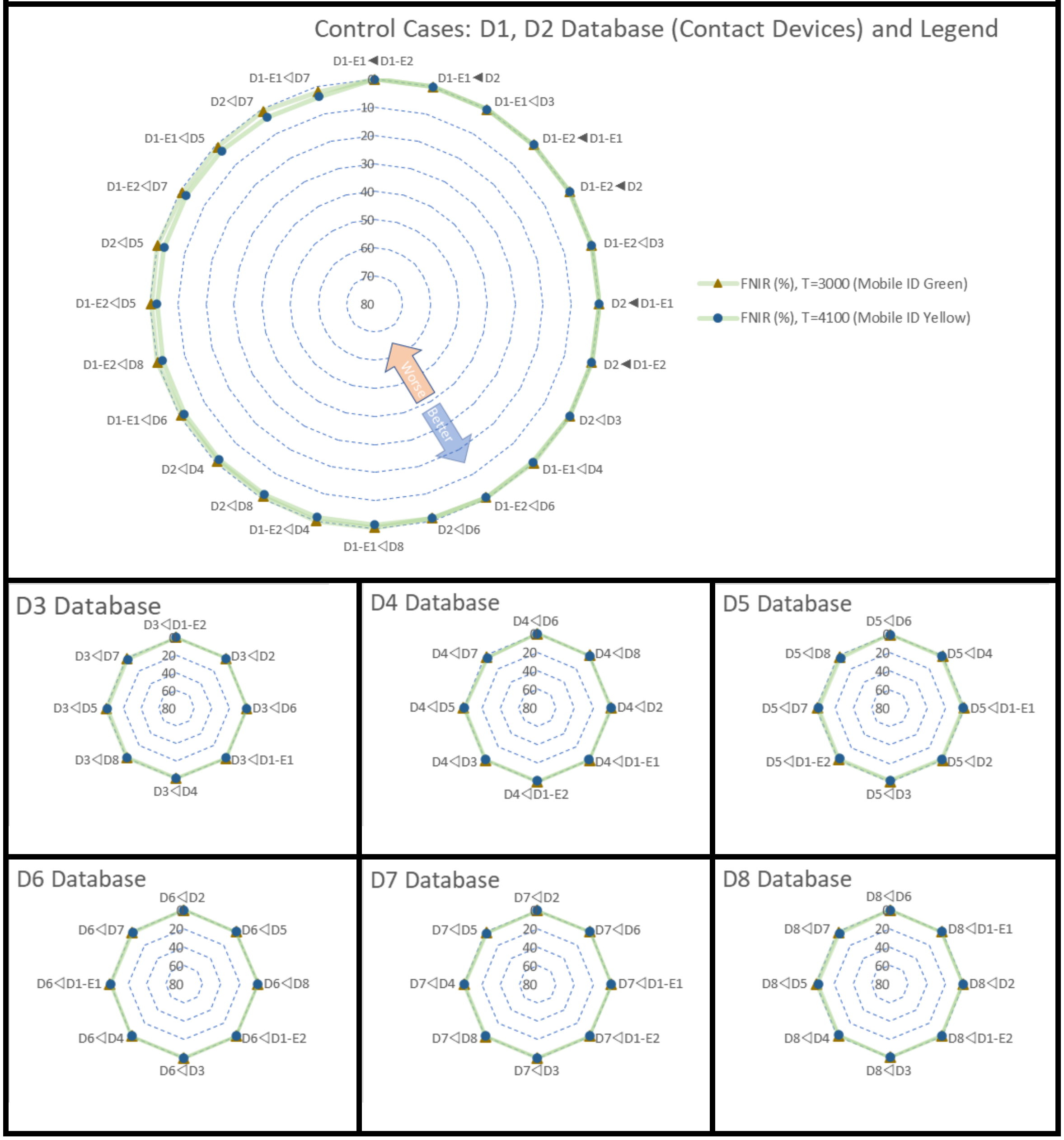
5.3.1. Findings for Objective 3

An examination of calculated accuracy data (see Figure 3 and Table 6) shows that at the high confidence threshold for Mobile ID (4100), almost one third of the test trials (#1 through #19) emerged equally as the best performing trials out of all 72 trials. For these 19 trials, FNIR was measured at 0 %.

Of these 19 trials, 4 of them, #10 (D3◁D1-E2), #11 (D3◁D2), #14 (D6◁D2) and #17 (D7◁D2) represent trials where a contactless capture device served as the biometric reference database for matching against a contact capture device and yielded error rates of 0 % at Mobile ID operating thresholds for FNIR indicating performance parity between some of the contactless capture device cases and contact capture devices.

5.3.2. Data for Objective 3

Figure 3: Accuracy of Contactless Database vs. Contactless Probes on Mobile ID Matcher at Operational Thresholds.



Legend:	D1: Contact, FTIR	D2: Contact, EL	D3: Contactless, Desktop	D4: Contactless Desktop	"◀": Contact Cases Only
	D5: Contactless Mobile Phone	D6: Contactless Mobile Phone	D7: Contactless Mobile Phone	D8: Contactless Mobile Phone	"◁": Contactless Cases

Table 6: Calculated Accuracy Data for Objective 3, Sorted in Ascending Order Of FNIR at T=4100.

Trial #	Database ◁ Probe	FNIR (%), T=3000 (Mobile ID Green)	FNIR (%), T=4100 (Mobile ID Yellow)
1	D1-E1◀D1-E2	0	0
2	D1-E1◀D2	0	0
3	D1-E1◁D3	0	0
4	D1-E2◀D1-E1	0	0
5	D1-E2◀D2	0	0
6	D1-E2◁D3	0	0
7	D2◀D1-E1	0	0
8	D2◀D1-E2	0	0
9	D2◁D3	0	0
10	D3◁D1-E2	0	0
11	D3◁D2	0	0
12	D3◁D6	0	0
13	D4◁D6	0	0
14	D6◁D2	0	0
15	D6◁D5	0	0
16	D6◁D8	0	0
17	D7◁D2	0	0
18	D7◁D6	0	0
19	D8◁D6	0	0
20	D1-E1◁D4	0	0.5
21	D3◁D1-E1	0	0.5
22	D4◁D8	0	0.5
23	D7◁D1-E1	0.5	0.5
24	D7◁D1-E2	0.5	0.5
25	D7◁D3	0	0.5
26	D7◁D8	0	0.5
27	D8◁D1-E1	0.5	0.5
28	D1-E2◁D6	0.6	0.6
29	D5◁D6	0.6	0.6
30	D6◁D1-E2	0.6	0.6
31	D6◁D3	0	0.6
32	D6◁D4	0.6	0.6
33	D4◁D2	0	0.8
34	D8◁D2	0.8	0.8
35	D2◁D6	1	1
36	D3◁D4	0.5	1
37	D4◁D1-E1	0	1
38	D4◁D1-E2	0	1
39	D4◁D3	0	1
40	D4◁D5	0	1
41	D5◁D4	0	1
42	D7◁D4	0.5	1
43	D8◁D1-E2	0.5	1
44	D8◁D3	0.5	1
45	D6◁D1-E1	0	1.2
46	D1-E1◁D8	0.5	1.5
47	D1-E2◁D4	0	1.5
48	D3◁D8	0.5	1.5
49	D5◁D1-E1	0.5	1.5
50	D2◁D8	0.8	1.6
51	D5◁D2	0	1.6
52	D2◁D4	0.8	1.7
53	D1-E1◁D6	0.6	1.8
54	D6◁D7	0.6	1.8
55	D1-E2◁D8	0	2
56	D5◁D3	0.5	2
57	D7◁D5	1.5	2
58	D8◁D4	1	2
59	D1-E2◁D5	0.5	2.5
60	D2◁D5	0	2.5
61	D3◁D5	0.5	2.5
62	D3◁D7	0.5	2.5
63	D5◁D1-E2	1	2.5
64	D5◁D7	1	2.5
65	D8◁D5	0	2.5
66	D1-E2◁D7	1	2.6
67	D8◁D7	1	3
68	D1-E1◁D5	1	3.1
69	D2◁D7	0.8	3.3
70	D1-E1◁D7	2	3.6
71	D4◁D7	3	4
72	D5◁D8	2	4

Legend:	D1: Contact, FTIR	D2: Contact, EL	D3: Contactless, Desktop	D4: Contactless Desktop	"◀": Contact Cases Only
	D5: Contactless Mobile Phone	D6: Contactless Mobile Phone	D7: Contactless Mobile Phone	D8: Contactless Mobile Phone	"◁": Contactless Cases

5.4. Objective 4: Comparison of Ten-Print and Mobile ID Matcher Accuracy at Arbitrary Level-Set Threshold

Biometric reference database Composition:	**All 8 devices, two encounters for D1, 8 Fingers, full size**
Probe Set Composition:	All 8 devices, two encounters for D1, 8 Fingers, full size
Matching Threshold:	As defined in section 4.8 for Ten-Print caseloads.
Special Notes:	Also includes contact-to-contact cases for comparison
Number of test trials in this Objective:	P(9,2) x 2 = 144 (72 on Mobile ID, and 72 on Ten-Print)

The goal of this objective is to see if a Mobile ID matcher performs better than a Ten-Print matcher in terms of matching accuracy at the **same arbitrary level-set matching threshold**, using the same experimental data with no changes to the data to favor either matcher configuration.

5.4.1. Findings for Objective 4

Of the six control trials in this objective (defined as contact database, contactless probe, cases: D1-E2◀D2 , D1-E2◀D1-E1 , D1-E1◀D1-E2, D2◀D1-E1 , D2◀D1-E2), the FNIR data (see Table 7) showed three of these trials performing equally on both the Ten-Print and Mobile ID matchers (cases D1-E2◀D2 , D1-E2◀D1-E1 , D1-E1◀D1-E2). Two of the cases (D1-E1◀D1-E2, D2◀D1-E2) showed better performance on the Ten-Print matcher. One case showed inconsistent behavior (D2◀D1-E1) where at T=5 000 the case favored the Mobile ID matcher, but at T=12 000 favored the Ten-Print matcher.

Perhaps the most marked result is that of the 144 test cases, 62 performed better on the Mobile ID matcher to some degree, 68 demonstrated no advantage between the Ten-Print and Mobile ID matcher and performed equally, while 14 cases showed better performance on the Ten-Print matcher. These results suggest that optimizations in place for the Mobile ID operation mode may also provide the matcher a performance advantage when processing contactless fingerprint imagery.

5.4.2. Data for Objective 4

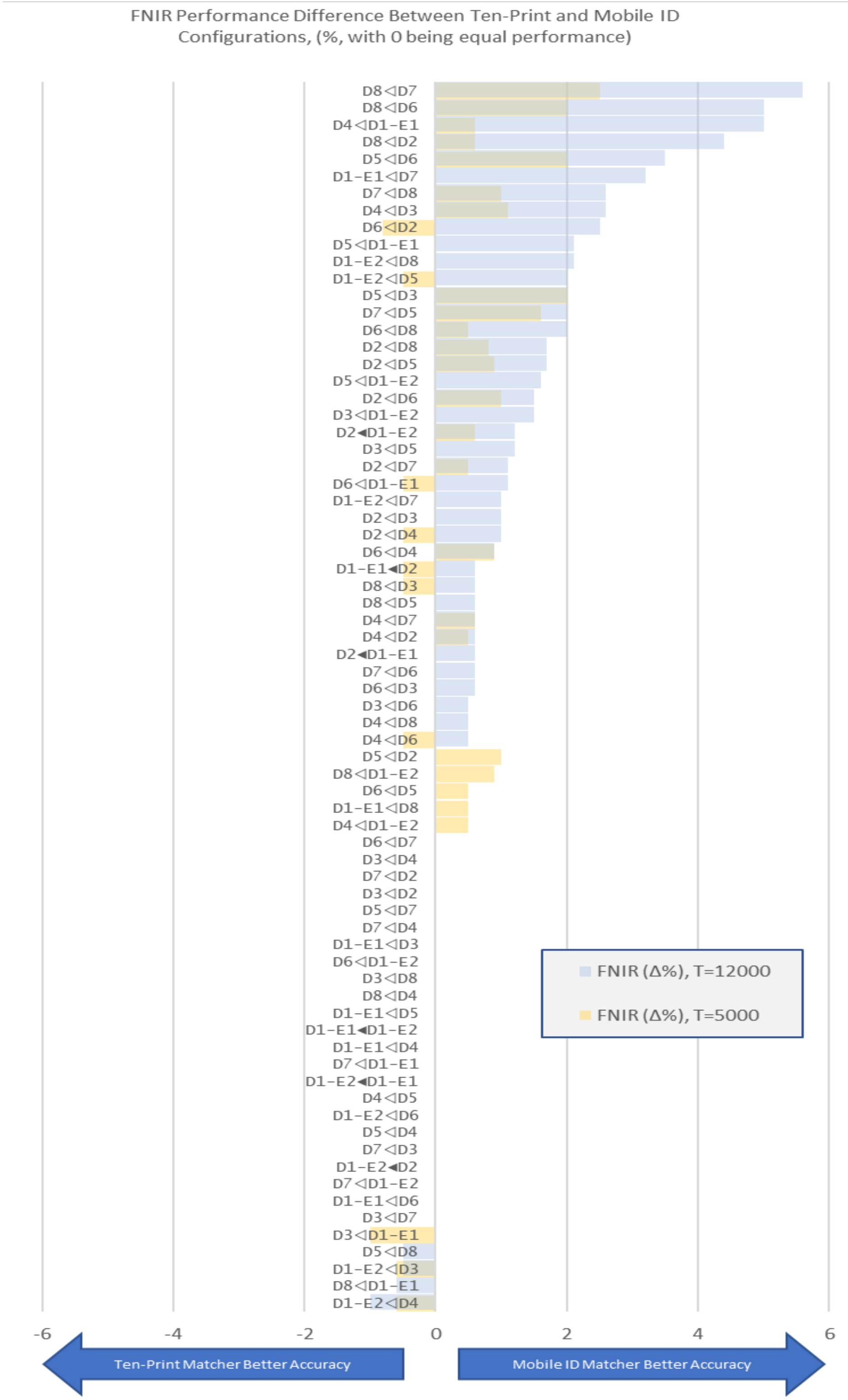


Figure 4: FNIR Variation Between Ten-Print Matcher and Mobile ID Matcher at Same Threshold.

Table 7: Error Variation (Δ%), Ten-Print vs. Mobile ID at Same Threshold (Positive Δ% → Mobile ID better)[3]

Database ◁ Probe	FNIR (Δ%), T=5000	FNIR (Δ%), T=12000
D1-E2◁D4	-0.6	-1
D8◁D1-E1	0	-0.6
D1-E2◁D3	-0.6	-0.5
D5◁D8	0	-0.5
D3◁D1-E1	-1	0
D3◁D7	0	0
D1-E1◁D6	0	0
D7◁D1-E2	0	0
D1-E2◀D2	0	0
D7◁D3	0	0
D5◁D4	0	0
D1-E2◁D6	0	0
D4◁D5	0	0
D1-E2◀D1-E1	0	0
D7◁D1-E1	0	0
D1-E1◁D4	0	0
D1-E1◀D1-E2	0	0
D1-E1◁D5	0	0
D8◁D4	0	0
D3◁D8	0	0
D6◁D1-E2	0	0
D1-E1◁D3	0	0
D7◁D4	0	0
D5◁D7	0	0
D3◁D2	0	0
D7◁D2	0	0
D3◁D4	0	0
D6◁D7	0	0
D4◁D1-E2	0.5	0
D1-E1◁D8	0.5	0
D6◁D5	0.5	0
D8◁D1-E2	0.9	0
D5◁D2	1	0
D4◁D6	-0.5	0.5
D4◁D8	0	0.5
D3◁D6	0	0.5
D6◁D3	0	0.6
D7◁D6	0	0.6
D2◀D1-E1	0	0.6
D4◁D2	0.5	0.6
D4◁D7	0.6	0.6
D8◁D5	0	0.6
D8◁D3	-0.5	0.6
D1-E1◀D2	-0.5	0.6
D6◁D4	0.9	0.9
D2◁D4	-0.5	1
D2◁D3	0	1
D1-E2◁D7	0	1
D6◁D1-E1	-0.5	1.1
D2◁D7	0.5	1.1
D3◁D5	0	1.2
D2◀D1-E2	0.6	1.2
D3◁D1-E2	0	1.5
D2◁D6	1	1.5
D5◁D1-E2	0	1.6
D2◁D5	0.9	1.7
D2◁D8	0.8	1.7
D6◁D8	0.5	2
D7◁D5	1.6	2
D5◁D3	2	2
D1-E2◁D5	-0.5	2
D1-E2◁D8	0	2.1
D5◁D1-E1	0	2.1
D6◁D2	-0.8	2.5
D4◁D3	1.1	2.6
D7◁D8	1	2.6
D1-E1◁D7	0	3.2
D5◁D6	2	3.5
D8◁D2	0.6	4.4
D4◁D1-E1	0.6	5
D8◁D6	2	5
D8◁D7	2.5	5.6

[3] Error data for deriving this table can be found in Table 11 in Appendix A.

Legend:	D1: Contact, FTIR	D2: Contact, EL	D3: Contactless, Desktop	D4: Contactless Desktop	"◀": Contact Cases Only
	D5: Contactless Mobile Phone	D6: Contactless Mobile Phone	D7: Contactless Mobile Phone	D8: Contactless Mobile Phone	"◁": Contactless Cases

5.5. Objective 5: Comparison of Matcher Throughput (Ten-Print vs. Mobile ID matcher)

Biometric Reference Database Composition:	**All 8 devices, two encounters for D1, 8 fingers, full size**
Probe Set Composition:	All 8 devices, two encounters for D1, 8 fingers, full size
Matching Threshold:	N/A
Special Notes:	Also includes contact-to-contact cases for comparison
Number of test trials in this Objective:	P(9,2) x 2 = 144 (72 on Mobile ID, and 72 on Ten-Print)

While the other objectives in this study were primarily focused on measuring the accuracy of the matchers vis-à-vis the introduction of contactless fingerprint imagery into the eco-system, another important operational concern is the throughput of the matcher under similar constraints. A matcher with perfect accuracy may be of limited utility if the amount of time it consumes in conducting searches increases substantially.

The goal of this objective is to see if a Mobile ID matcher performs better in terms of transactional throughput when compared to a Ten-Print matcher, using the same experimental data with no changes to the data to favor either matcher.

5.5.1. Findings for Objective 5

Of the six control trials in this objective (defined as contact database, contactless probe, cases: D1-E2◄D2 , D1-E2◄D1-E1 , D1-E1◄D1-E2, D2◄D1-E1 , D2◄D1-E2), throughput data (see Table 8) showed only one of these six trials (D2◄D1-E2) performed better on the Mobile ID matcher with respect to search throughput. All other control cases exhibited faster throughput on the Ten-Print matcher.

Of all 72 comparison trials run on each matcher configuration, 37 of them showed better throughput on the Mobile ID matcher while 35 performed better on the Ten-Print matcher (see Figure 5).

For the 37 cases that performed better on the Mobile ID matcher, the average search time for each transaction for the Mobile ID matcher was 35 871 ms vs. 43 288 ms for the Ten-Print matcher.

Of the 35 cases that performed better on the Ten-Print matcher, the average search time for each transaction for the Ten-Print matcher was 34 039 ms vs. 36 306 ms for the Mobile ID matcher.

These results suggest that while there are cases where the Ten-Print matcher exhibits better throughput than the Mobile ID matcher, cases that are more challenging to the matcher seem to incur a greater penalty on average on the Ten-Print matcher than the Mobile ID matcher (7 417 ms average penalty for poorly performing Ten-Print cases vs. 2 267 ms average penalty for poorly performing Mobile ID cases).

5.5.2. Data for Objective 5

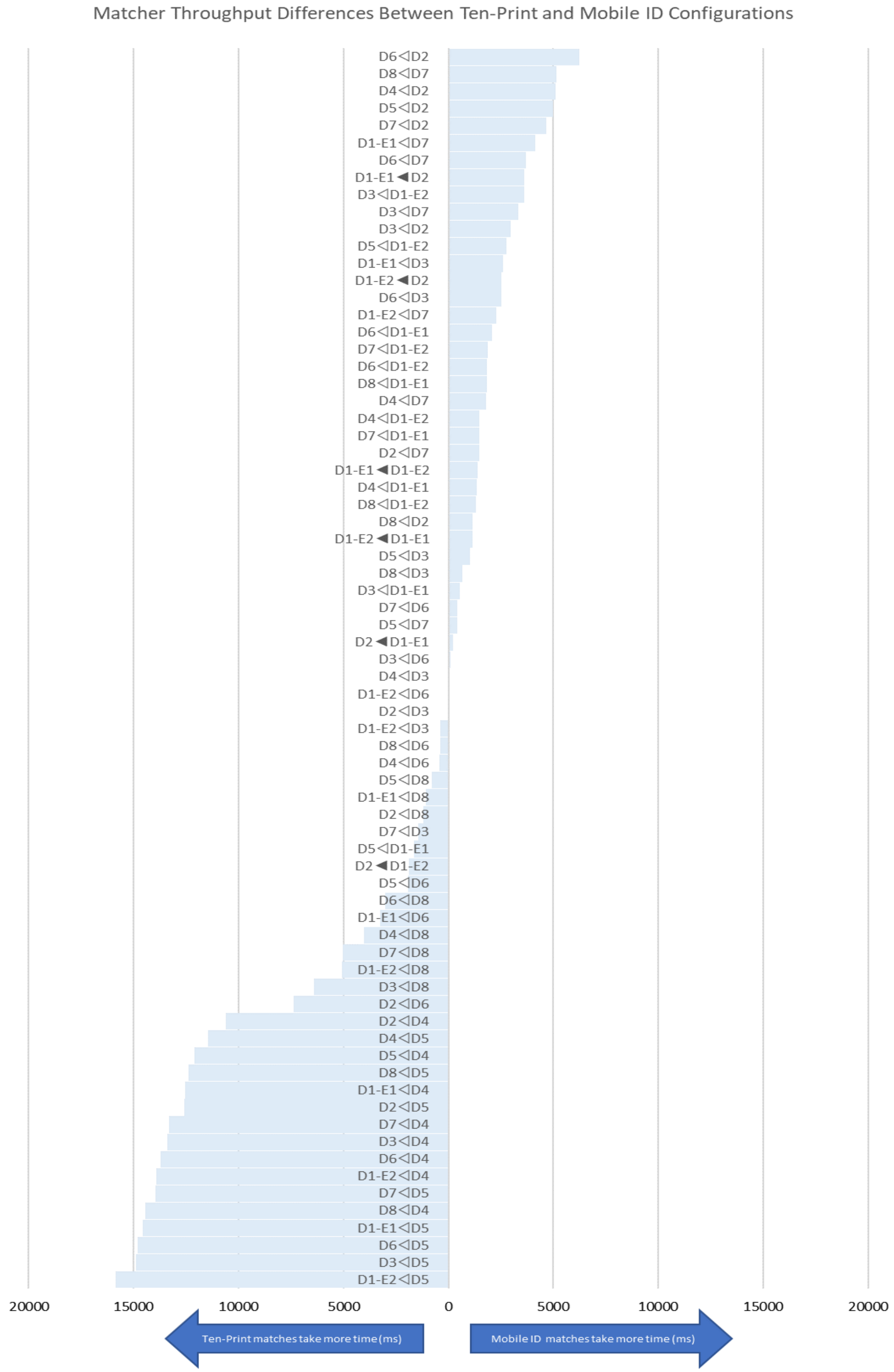


Figure 5: Matcher Throughput Variation Between Ten-Print and Mobile ID Configurations by Device Tested

Legend:	D1: Contact, FTIR	D2: Contact, EL	D3: Contactless, Desktop	D4: Contactless Desktop	"◀": Contact Cases Only
	D5: Contactless Mobile Phone	D6: Contactless Mobile Phone	D7: Contactless Mobile Phone	D8: Contactless Mobile Phone	"◁": Contactless Cases

Table 8: Performance Difference Between Ten-Print and Mobile ID Matcher by Case Tested (Sorted by Absolute Difference).

Database ◁ Probe	Avg Search Time ms, Ten-Print	Avg Search Time ms, Mobile ID	Difference ms
D1-E2◁D6	28865	28843	-22
D2◁D3	48951	48913	-39
D4◁D3	40662	40703	41
D3◁D6	29835	29933	98
D2◀D1-E1	26244	26460	215
D1-E2◁D3	42599	42224	-375
D8◁D6	29467	29075	-392
D5◁D7	36704	37113	409
D7◁D6	29438	29863	425
D4◁D6	28795	28366	-429
D3◁D1-E1	31311	31867	556
D8◁D3	42727	43376	650
D5◁D8	36949	36176	-773
D5◁D3	40652	41683	1032
D1-E1◁D8	36106	35023	-1083
D1-E2◀D1-E1	30600	31754	1154
D8◁D2	33893	35048	1155
D2◁D8	39596	38397	-1200
D8◁D1-E2	36781	38078	1297
D4◁D1-E1	30368	31704	1336
D1-E1◀D1-E2	36105	37506	1402
D7◁D3	41823	40381	-1442
D2◁D7	37060	38531	1470
D7◁D1-E1	28881	30353	1472
D4◁D1-E2	35989	37483	1493
D5◁D1-E1	31301	29653	-1649
D4◁D7	37525	39313	1788
D8◁D1-E1	29165	30992	1827
D6◁D1-E2	35570	37426	1856
D2◀D1-E2	39235	37362	-1874
D7◁D1-E2	36138	38025	1886
D5◁D6	28930	27028	-1901
D6◁D1-E1	29156	31252	2096
D1-E2◁D7	35598	37883	2285
D6◁D3	37564	40097	2532
D1-E2◀D2	33534	36073	2539
D1-E1◁D3	39521	42128	2607
D5◁D1-E2	35355	38106	2752
D3◁D2	34399	37353	2954
D6◁D8	34573	31575	-2998
D1-E1◁D6	31157	27920	-3237
D3◁D7	34869	38204	3335
D3◁D1-E2	35184	38798	3614
D1-E1◀D2	32802	36420	3618
D6◁D7	32435	36148	3713
D4◁D8	37749	33738	-4011
D1-E1◁D7	33662	37819	4157
D7◁D2	31857	36540	4683
D5◁D2	31747	36718	4972
D7◁D8	37640	32593	-5047
D1-E2◁D8	37756	32695	-5061
D4◁D2	32653	37753	5099
D8◁D7	32975	38105	5130
D6◁D2	30498	36740	6242
D3◁D8	38499	32097	-6402
D2◁D6	32409	25042	-7367
D2◁D4	53259	42675	-10585
D4◁D5	50739	39311	-11428
D5◁D4	50302	38224	-12078
D8◁D5	50986	38622	-12364
D1-E1◁D4	51878	39328	-12550
D2◁D5	54490	41924	-12566
D7◁D4	52281	38996	-13286
D3◁D4	52486	39080	-13405
D6◁D4	49257	35555	-13703
D1-E2◁D4	52417	38514	-13903
D7◁D5	52800	38859	-13941
D8◁D4	52688	38262	-14426
D1-E1◁D5	52344	37795	-14549
D6◁D5	50450	35664	-14786
D3◁D5	54322	39446	-14876
D1-E2◁D5	51984	36122	-15863

Legend:	D1: Contact, FTIR	D2: Contact, EL	D3: Contactless, Desktop	D4: Contactless Desktop	"◀": Contact Cases Only
	D5: Contactless Mobile Phone	D6: Contactless Mobile Phone	D7: Contactless Mobile Phone	D8: Contactless Mobile Phone	"◁": Contactless Cases

5.6. Objective 6: Examination of Self-Matching

Biometric Reference Database Composition:	**All 8 devices, two encounters for D1, 8 Fingers, full size.**
Probe Set Composition:	Same image set as biometric reference database.
Matching Threshold:	As defined in section 4.8 for Ten-Print caseloads.
Special Notes:	Probe and database pair are the same image/impression.
Number of test trials in this Objective:	18 (9 on Ten-Print matcher, and 9 on Mobile ID matcher)

Given NIST's experiences in large scale testing of matchers, there is anecdotal evidence that the case of self-matching usually represents a trivial challenge for any modern matcher and normally yields a very high biometric candidate score with zero error. Also given NIST's experience, there are cases where images of interest represent samples containing unusual systematic error (such as consistent occlusion of a portion of the image or some other aspect of the sample quality of the image) that hampers the self-matching of that image even if its successfully vectorized and enrolled.

This objective's goal is to conduct self-matching tests on an image against itself and observe any abnormalities in matcher behavior.

5.6.1. Findings for Objective 6

Data obtained in the self-matching trials indicated no unusual behavior in terms of error rates (see Table 9). Examination of the average biometric candidate scores (see Figure 6 and Table 10) for the self-matching trials however showed a different picture where contactless capture devices generally seemed to yield larger self-match scores than cases from contact images (average of 253 722 for contact based images vs. an average score of 394 687 for contactless fingerprint imagery). It is hypothesized that salient features not typically present in contact collected images are present in contactless captured images and these features may be used by the matcher to artificially strengthen the biometric candidate score.

Self-match throughput was similar (see Figure 7 and Table 10) in all trials except for D4 and D5 where the self-match cases took much longer (+32 % for D4, +37 % for D5) on the Ten-Print matcher vs. the Mobile ID matcher.

5.6.2. Data for Objective 6

Table 9: Accuracy of Each Matcher Configuration at Same Threshold for the Self-Matching Cases.

Ten-Print	FNIR (%) T=5000	FNIR (%) T=12000	Mobile ID	FNIR (%) T=5000	FNIR (%) T=12000
D1-E1◄D1-E1	0	0	D1-E1◄D1-E1	0	0
D1-E2◄D1-E2	0	0	D1-E2◄D1-E2	0	0
D2◄D2	0	0	D2◄D2	0	0
D3◁D3	0	0	D3◁D3	0	0
D4◁D4	0	0	D4◁D4	0	0
D5◁D5	0	0	D5◁D5	0	0
D6◁D6	0	0	D6◁D6	0	0
D7◁D7	0	0	D7◁D7	0	0
D8◁D8	0	0	D8◁D8	0	0

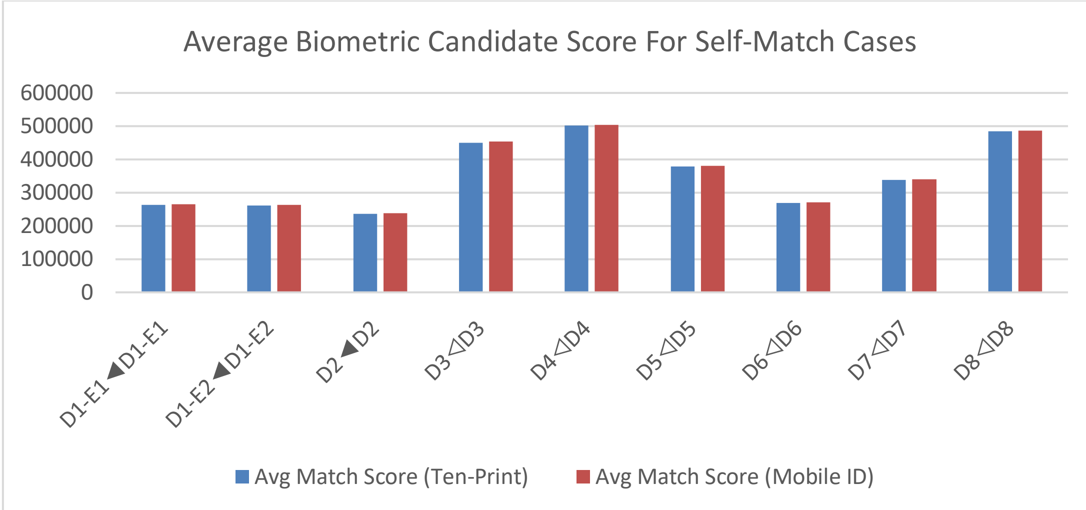


Figure 6: Average Biometric Candidate Scores Returned for Self-Matching Tests at Level-Set Threshold.

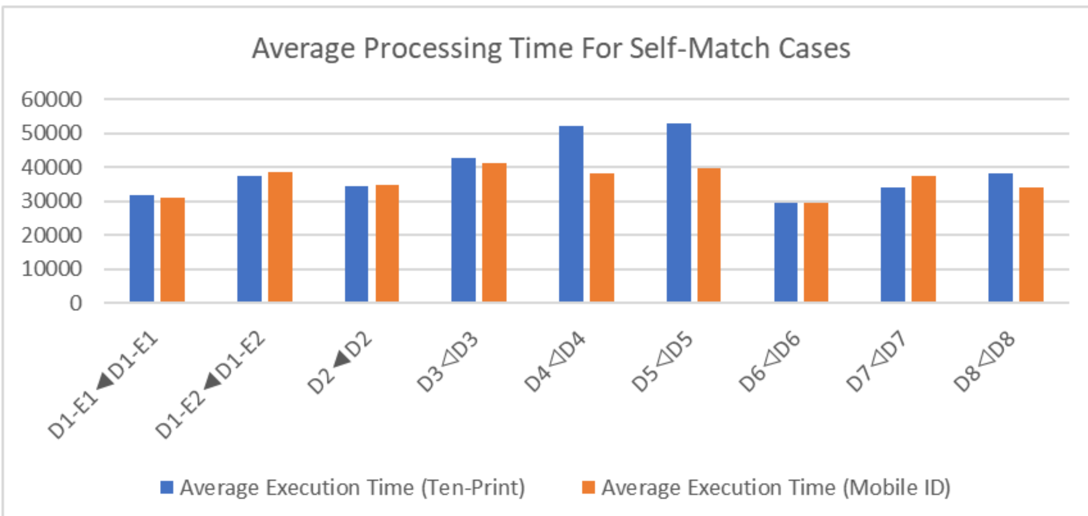


Figure 7: Average Processing Time for Self-Matching Tests at Level-Set Threshold.

Table 10: Data Tables for Average Biometric Candidate Score and Execution Times for the Self-Match Cases.

Case	Avg Biometric Candidate Score (Ten-Print)	Avg Biometric Candidate Score (Mobile ID)	Avg Execution Time, ms (Ten-Print)	Avg Execution Time, ms (Mobile ID)
D1-E1◀D1-E1	263328	265033	31854	31080
D1-E2◀D1-E2	261603	263305	37386	38509
D2◀D2	236235	237783	34447	34995
D3◁D3	450767	452870	42762	41079
D4◁D4	502665	504523	52391	38125
D5◁D5	378254	380248	52783	39754
D6◁D6	269615	271304	29400	29545
D7◁D7	337987	339682	34020	37447
D8◁D8	484914	486803	38043	34206

Legend:	D1: Contact, FTIR	D2: Contact, EL	D3: Contactless, Desktop	D4: Contactless Desktop	"◀": Contact Cases Only
	D5: Contactless Mobile Phone	D6: Contactless Mobile Phone	D7: Contactless Mobile Phone	D8: Contactless Mobile Phone	"◁": Contactless Cases

6. Conclusions

This study set out to examine the various ways a state-of-industry high end commercial law enforcement grade matcher can be impacted by the introduction of contactless fingerprint imagery. Furthermore, it set out to examine the behavior of such images on a traditional Ten-Print law enforcement grade matcher as well as an equally sophisticated matcher with optimizations specifically for Mobile ID case-loads.

On a Ten-Print matcher configured for thresholds typical of operation within a law enforcement environment, the contact-to-contact control trials (6 of 72 total experimental treatments, Table 5) emerged as most accurate, with the FNIR ranging from 0 % to 0.5 % in these 6 trials. The remaining 66 trials represented a mix of contactless-to-contact or contactless-to-contactless trials. Of the remaining 66 trials, the D3 emerged as the highest performing contactless capture device. Trial #7 (Appendix F certified D2 contact-database, D3 contactless probes) and Trial #8 (D3 contactless database, Appendix F certified D2 contact-probes) yielded an FNIR of 1.6 % at the lights-out threshold.

On a Mobile ID matcher configured for thresholds typical of operation within a law enforcement environment, accuracy measurements showed almost one third of the test trials (#1 through #19) tied as the best performing trials (in terms of accuracy) out of all 72 trials (see Table 6) with FNIR of 0 %. Of the 19 trials tied as highest performing, D3 again emerged as the best performing contactless capture device with respect to accuracy (in case #4 with D3 as the best performing contactless probe, and case #10 with D3 as the best performing contactless capture device).

Given the measured performance differences between the Ten-Print and the Mobile ID matcher at their respective operational thresholds, a further examination of these two matchers was conducted at the same level set threshold. Results of this examination showed that of the 144 test trials, 62 performed better on the Mobile ID matcher to some degree, 68 demonstrated no advantage between the Ten-Print and Mobile ID matcher and performed equally, while 14 cases showed better performance on the Ten-Print matcher (see Figure 4). These results suggest that optimizations in place for the Mobile ID operation mode may also provide a performance advantage when processing contactless fingerprint imagery.

Examination of matcher throughputs showed a different issue. Of the 6 control trials (contact to contact), most (5 of 6) showed a performance advantage on the Ten-Print matcher, and one of the 6 trials showed a small throughput advantage on the Mobile ID matcher (see Table 8). Trials that performed poorly on the Ten-Print matcher (mostly contactless cases) showed a greater throughput penalty (7 417 ms average) than trials that performed poorly on the Mobile ID matcher (2 267 ms average penalty). This reinforces that the Ten-Print matcher was built to perform quickly and accurately on contact-to-contact cases, and when contactless fingerprint imagery is introduced into that eco-system the matcher incurs greater penalties in terms of both performance and throughput versus the Mobile ID matcher.

This study also examined the commonly trivial case of matching images to themselves. Accuracy data obtained indicated no unusual behavior in terms of error rates (see Table 9), but the average biometric candidate scores obtained for the self-matching cases showed that images from contactless capture devices generally yielded higher self-match biometric candidate scores than those from contact images (average of 253 722 for contact based images vs. an average score of 394 687 for contactless fingerprint imagery). It is hypothesized that additional salient features within the contactless samples not typically present in contact collected images may be used by the matcher to artificially strengthen the biometric candidate score.

7. Acknowledgements

This study would not have been possible without the help from the many people that helped make it a possibility and a success. First, we would like to thank Mary F. Theofanos and Susanne M. Furman for their vital assistance on the collection of data used in this study. Next, we would like to thank Gregory P. Fiumara, Patrick J. Grother, and John M. Splain for their time, advice, and candor in reviewing the contents of this study, and providing many meaningful suggestions to help make this a better report. Finally, we would like to thank the 200 Federal employees who volunteered their time and biometric data to make this study possible.

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APPENDIX A. SUPPLEMENTAL TEST DATA

Table 11: Error Data From the Ten-Print and Mobile ID Matchers at The Same Arbitrary Thresholds.

Database ◁ Probe	FNIR (%), Ten-Print, T=5000	FNIR (%), Ten-Print, T=12000	FNIR (%), Mobile ID, T=5000	FNIR (%), Mobile ID, T=12000
D1-E1◀D2	0	0	0	0
D1-E2◀D2	0	0	0	0
D2◀D1-E1	0	0	0	0
D2◀D1-E2	0	0	0	0
D2◁D3	0	0.8	0	0.8
D3◁D2	0	0.8	0	0.8
D1-E1◀D1-E2	0.5	0.5	0.5	0.5
D1-E2◀D1-E1	0.5	0.5	0.5	0.5
D6◁D2	0	1	0	1
D6◁D8	0	1.2	0	1.2
D8◁D6	0	1.8	0	1.2
D1-E2◁D3	0	3.6	0	3.1
D2◁D6	1	3	1	2
D3◁D1-E2	0	3.6	0	3.6
D1-E1◁D3	1	3.1	1	3.1
D3◁D1-E1	1	3.1	1	3.1
D4◁D2	1.7	4.2	0.8	2.5
D6◁D5	1.2	6.2	0.6	5
D6◁D3	0.6	6.2	0.6	6.2
D4◁D1-E2	2	6.2	1	4.7
D3◁D6	0.6	6.8	0.6	6.8
D5◁D6	1.2	6.8	1.2	5.6
D4◁D3	1.5	6.1	1.5	6.1
D4◁D1-E1	1.5	6.8	1	6.2
D2◁D4	1.7	5.9	1.7	5.9
D1-E1◁D4	1.5	6.8	1	5.7
D6◁D1-E2	0.6	7.5	0.6	8.1
D6◁D1-E1	1.2	7.5	1.2	6.9
D1-E2◁D6	1.2	8.1	0.6	7.5
D1-E2◁D4	2	5.7	2.6	6.2
D3◁D4	2	6.6	1.5	6.6
D8◁D2	1.6	9.3	0.8	7.6
D1-E1◁D6	1.8	8.1	1.8	8.1
D7◁D2	0.8	10	1.6	7.5
D4◁D6	1.2	9.4	1.2	8.8
D7◁D1-E1	1	9.8	0.5	9.8
D6◁D4	0.6	10.7	0.6	10.1
D7◁D1-E2	0.5	11.9	0.5	9.8
D8◁D1-E2	1.5	9.9	1.5	9.9
D8◁D3	2.5	10.2	1.5	10.2
D2◁D8	2.5	11	1.6	10.1
D8◁D1-E1	2	10.4	2	10.9
D7◁D6	1.8	13.8	1.2	8.8
D7◁D3	2	12.1	2	10.6
D1-E2◁D8	2.6	10.9	2.6	10.9
D7◁D8	4.5	13.2	2	7.6
D3◁D8	2	11.7	2	11.7
D4◁D5	1.5	13.1	2	12.1
D1-E1◁D8	2	12.5	2	12.5
D8◁D5	3	12.6	3	12.1
D4◁D8	2.5	13.8	2	13.8
D5◁D3	2.5	14.1	2.5	13.1
D5◁D2	2.5	15.1	1.6	15.1
D7◁D5	2	16.1	2.5	14.1
D5◁D8	4	14.2	4.5	13.7
D5◁D1-E1	3.6	16.5	2.5	13.9
D8◁D4	3.5	14.8	4.1	15.8
D3◁D5	3	15.6	4	15.6
D5◁D4	4.5	17.2	2.5	15.2
D2◁D5	3.3	16.8	3.3	16.8
D5◁D1-E2	3.1	17.6	3.6	17
D8◁D7	5.6	17.3	4	15.3
D1-E1◁D5	3.6	17.6	4.1	17
D1-E2◁D5	4.1	19.6	3.1	17
D7◁D4	4.5	19.3	4	17.3
D2◁D7	4.2	22.6	4.2	21
D6◁D7	6.2	23.2	5.6	18.8
D3◁D7	6	25.8	4	22.3
D5◁D7	5.5	27.7	3.5	22.7
D1-E2◁D7	4.6	27.6	4.6	24.4
D1-E1◁D7	5.7	30.7	6.2	29.6
D4◁D7	9.1	30.6	9.1	28.5

Legend:	D1: Contact, FTIR	D2: Contact, EL	D3: Contactless, Desktop	D4: Contactless Desktop	"◀": Contact Cases Only
	D5: Contactless Mobile Phone	D6: Contactless Mobile Phone	D7: Contactless Mobile Phone	D8: Contactless Mobile Phone	"◁": Contactless Cases

APPENDIX B. TEST DATA STATISTICS

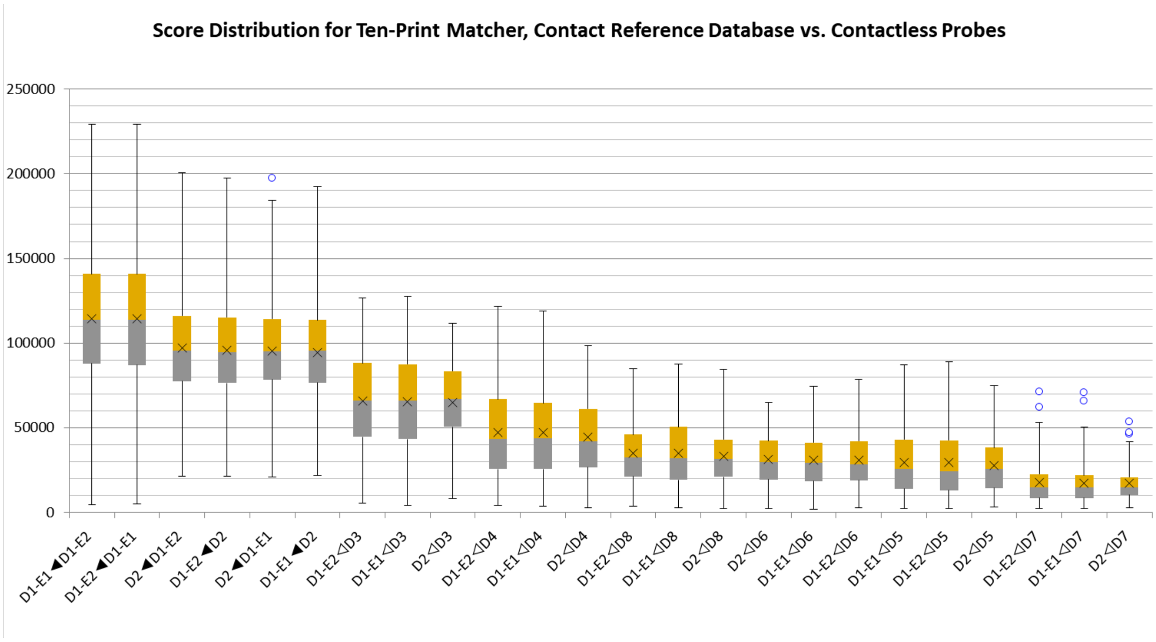

Figure 8: Boxplots Showing Score Distribution for Ten-Print Matcher using Contact Reference Database vs. Contactless Probes.

Table 12: Score Distribution Summary Statistics for Ten-Print Matcher using Contact Reference Database vs. Contactless Probes.

	Minimum	Mean	Median	Maximum	Standard Deviation	Standard Error	Kurtosis	Skewness	Count
D1-E1◀D1-E2	4709	114403.2	113552.0	229254	39643.6	2853.6	-0.2	0.0	193
D1-E2◀D1-E1	4893	114305.3	113915.0	229242	39510.5	2844.0	-0.2	0.0	193
D2◀D1-E2	21189	96963.3	95705.0	200644	32723.7	3012.5	0.3	0.2	118
D1-E2◀D2	21237	95717.2	94486.5	197477	32224.6	2966.5	0.3	0.2	118
D2◀D1-E1	20809	95351.2	95263.0	197659	31241.7	2876.0	0.7	0.3	118
D1-E1◀D2	21607	94213.7	95347.0	192272	30639.2	2820.6	0.6	0.2	118
D1-E2◁D3	5252	65874.0	66162.5	126849	29497.3	2140.0	-0.8	-0.1	190
D1-E1◁D3	4088	65477.2	66184.0	127719	29509.5	2140.8	-0.8	-0.1	190
D2◁D3	8228	64731.7	66758.0	111602	25336.8	2332.4	-0.7	-0.2	118
D1-E2◁D4	3927	47364.0	43123.5	121801	26603.0	1971.9	-0.4	0.5	182
D1-E1◁D4	3465	47105.9	43934.0	118825	25904.1	1914.9	-0.5	0.5	183
D2◁D4	2607	44288.2	42067.0	98433	24061.0	2263.5	-0.6	0.4	113
D1-E2◁D8	3455	35154.3	32649.5	84677	19828.1	1469.8	-0.2	0.6	182
D1-E1◁D8	2516	35124.0	32192.0	87377	20182.7	1491.9	-0.4	0.5	183
D2◁D8	2449	33126.9	31611.5	84274	18004.1	1686.2	-0.1	0.5	114
D2◁D6	2312	31308.9	29726.0	65100	14073.9	1443.9	-0.5	0.5	95
D1-E1◁D6	1899	30744.5	29446.0	74322	15216.4	1214.4	-0.1	0.5	157
D1-E2◁D6	2504	30686.3	28154.5	78550	15539.1	1244.1	0.1	0.6	156
D1-E1◁D5	2239	29443.5	25484.0	87355	19110.1	1428.4	0.0	0.8	179
D1-E2◁D5	2345	29379.4	24341.0	89069	19863.8	1484.7	0.1	0.8	179
D2◁D5	3216	27750.9	25420.0	74667	16369.8	1539.9	-0.4	0.6	113
D1-E2◁D7	2360	17618.2	14722.0	71245	12057.3	1015.4	3.3	1.6	141
D1-E1◁D7	2107	17405.4	14683.0	70973	12253.1	1010.6	3.2	1.6	147
D2◁D7	2926	17041.9	14522.0	53653	10573.7	1167.7	1.9	1.4	82

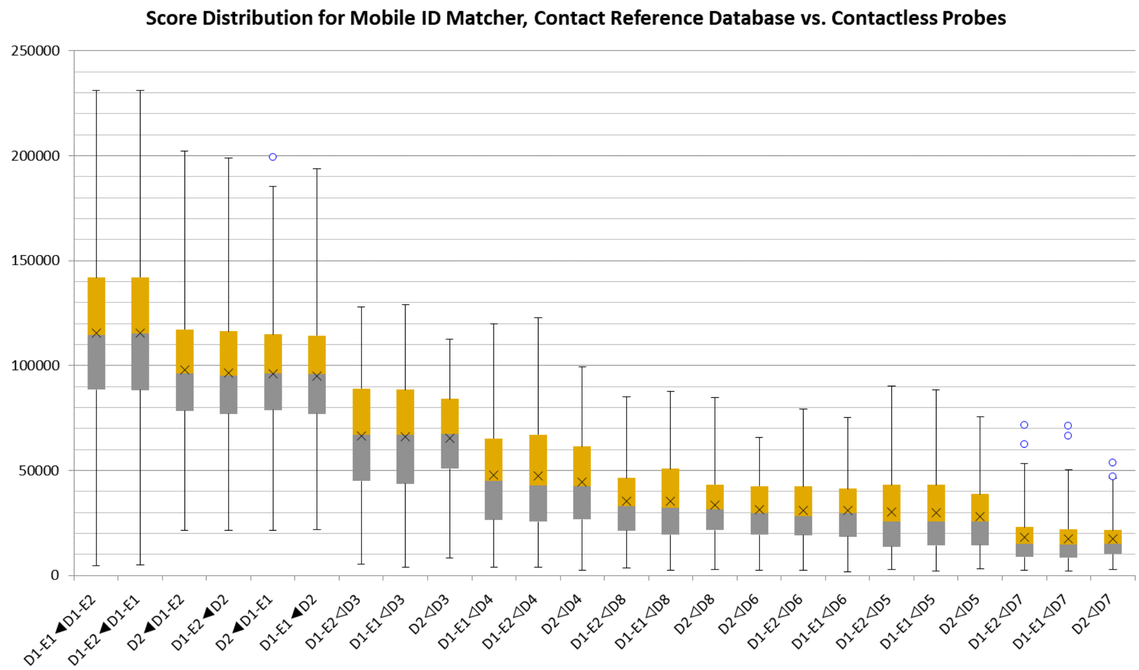

Figure 9: Boxplots Showing Score Distribution for Mobile ID Matcher using Contact Reference Database vs. Contactless Probes.

Table 13: Score Distribution Summary Statistics for Mobile ID Matcher using Contact Reference Database vs. Contactless Probes.

	Minimum	Mean	Median	Maximum	Standard Deviation	Standard Error	Kurtosis	Skewness	Count
D1-E1◀D1-E2	4733	115400.0	114494.0	231002	39928.7	2874.1	-0.2	0.0	193
D1-E2◀D1-E1	4909	115308.4	115136.0	231009	39784.9	2863.8	-0.2	0.0	193
D2◀D1-E2	21436	97754.0	96466.5	202155	32952.2	3033.5	0.3	0.2	118
D1-E2◀D2	21522	96499.4	95156.0	198978	32440.4	2986.4	0.3	0.2	118
D2◀D1-E1	21328	96131.2	96156.0	199143	31444.7	2894.7	0.7	0.3	118
D1-E1◀D2	21864	94977.0	95975.5	193724	30848.0	2839.8	0.5	0.2	118
D1-E2◁D3	5305	66558.0	66864.5	127996	29822.5	2163.5	-0.8	-0.1	190
D1-E1◁D3	4111	66159.7	66883.5	128860	29827.9	2163.9	-0.8	-0.1	190
D2◁D3	8241	65361.1	67470.5	112628	25599.2	2356.6	-0.7	-0.2	118
D1-E1◁D4	3844	47751.5	44996.0	119960	26014.3	1928.3	-0.5	0.5	182
D1-E2◁D4	3936	47534.9	42841.0	122915	26975.2	1994.1	-0.4	0.5	183
D2◁D4	2618	44645.7	42349.0	99278	24257.8	2282.0	-0.6	0.4	113
D1-E2◁D8	3464	35412.1	32951.5	85056	20000.5	1482.5	-0.2	0.6	182
D1-E1◁D8	2525	35376.6	32358.0	87827	20353.6	1504.6	-0.4	0.5	183
D2◁D8	2719	33616.6	31725.0	84702	17988.8	1692.2	-0.1	0.6	113
D2◁D6	2316	31534.3	29866.0	65795	14186.8	1455.5	-0.5	0.5	95
D1-E2◁D6	2516	31111.7	28355.0	79109	15584.3	1251.8	0.1	0.6	155
D1-E1◁D6	1904	30992.2	29723.0	75126	15347.5	1224.9	-0.1	0.5	157
D1-E2◁D5	2999	30159.0	25511.5	90147	19931.1	1502.4	0.1	0.8	176
D1-E1◁D5	2246	29724.3	25679.0	88390	19331.0	1444.9	0.0	0.8	179
D2◁D5	3228	28003.4	25534.0	75653	16513.7	1553.5	-0.4	0.6	113
D1-E2◁D7	2368	18126.5	14919.0	71629	12283.3	1057.2	3.0	1.5	135
D1-E1◁D7	2181	17641.5	14810.5	71401	12459.4	1038.3	3.0	1.5	144
D2◁D7	2935	17415.1	14998.5	53825	10839.4	1227.3	1.6	1.3	78

Legend:	D1: Contact, FTIR	D2: Contact, EL	D3: Contactless, Desktop	D4: Contactless Desktop	"◀": Contact Cases Only
	D5: Contactless Mobile Phone	D6: Contactless Mobile Phone	D7: Contactless Mobile Phone	D8: Contactless Mobile Phone	"◁": Contactless Cases

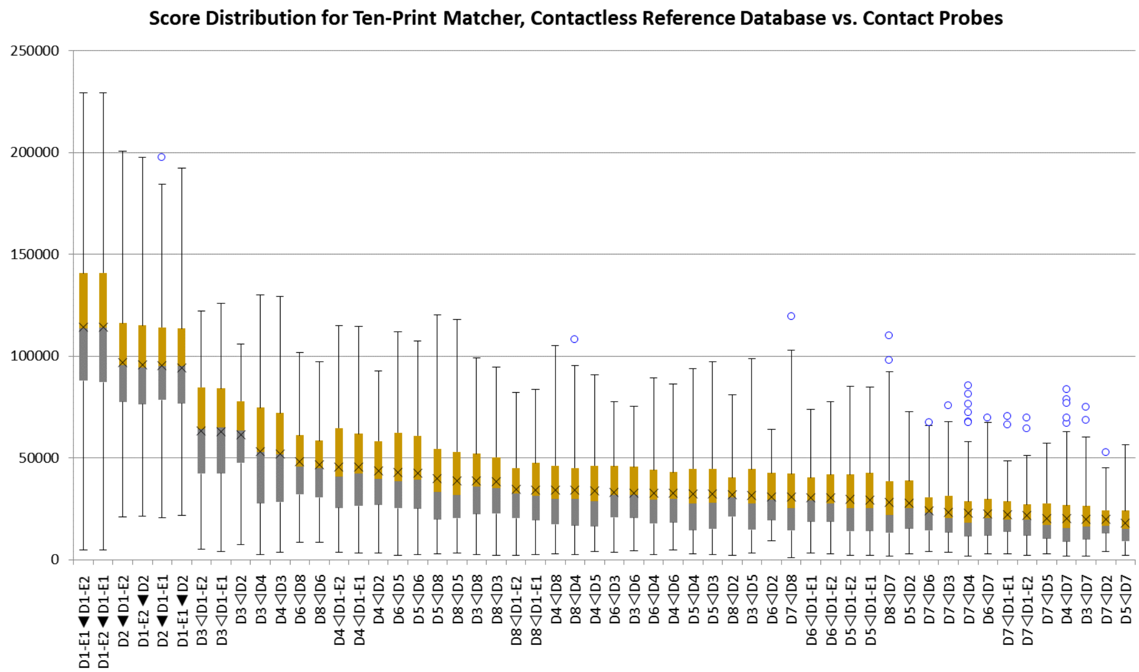

Figure 10: Boxplots Showing Score Distribution for Ten-Print Matcher, Contactless Reference Database vs. Contact Probes.

Table 14: Score Distribution Summary Statistics for Ten-Print Matcher, Contactless Reference Database vs. Contact Probes.

	Minimum	Mean	Median	Maximum	Standard Deviation	Standard Error	Kurtosis	Skewness	Count
D1-E1◀D1-E2	4709	114403.2	113552.0	229254	39643.6	2853.6	-0.2	0.0	193
D1-E2◀D1-E1	4893	114305.3	113915.0	229242	39510.5	2844.0	-0.2	0.0	193
D2◀D1-E2	21189	96963.3	95705.0	200644	32723.7	3012.5	0.3	0.2	118
D1-E2◀D2	21237	95717.2	94486.5	197477	32224.6	2966.5	0.3	0.2	118
D2◀D1-E1	20809	95351.2	95263.0	197659	31241.7	2876.0	0.7	0.3	118
D1-E1◀D2	21607	94213.7	95347.0	192272	30639.2	2820.6	0.6	0.2	118
D3◁D1-E2	5068	63249.5	64081.0	122172	27960.5	2028.5	-0.8	-0.1	190
D3◁D1-E1	4020	62864.8	65130.0	125928	28041.7	2034.4	-0.7	-0.1	190
D3◁D2	7484	61223.8	63400.0	106112	23724.3	2184.0	-0.7	-0.2	118
D3◁D4	2411	53273.2	52811.0	130194	29772.8	2165.7	-0.7	0.3	189
D4◁D3	3556	51879.5	51595.5	129502	28744.1	2107.6	-0.6	0.3	186
D6◁D8	8688	48111.6	45714.0	101944	21679.2	1724.7	-0.3	0.5	158
D8◁D6	8744	46510.0	44961.0	97115	21001.9	1670.8	-0.3	0.5	158
D4◁D1-E2	3489	45567.8	40719.5	115075	25168.5	1886.5	-0.5	0.5	178
D4◁D1-E1	3452	45412.9	42383.0	114518	24650.4	1847.6	-0.5	0.4	178
D4◁D2	3322	43619.1	39640.0	92761	22091.1	2176.7	-0.7	0.3	103
D6◁D5	2282	42728.8	38540.0	112135	23172.0	1849.3	-0.5	0.5	157
D5◁D6	2589	42640.6	39461.0	107288	22959.2	1832.3	-0.6	0.5	157
D5◁D8	2744	39738.1	33212.5	120129	26354.6	1912.0	0.0	0.8	190
D8◁D5	3108	38930.0	31924.0	118150	25436.4	1865.1	0.0	0.8	186
D3◁D8	2392	38879.5	35937.0	99120	22100.2	1607.6	-0.2	0.6	189
D8◁D3	2274	38226.7	35026.0	94460	21176.5	1561.2	-0.2	0.5	184
D8◁D1-E2	2296	34524.7	32507.5	82177	18665.3	1415.0	-0.2	0.6	174
D8◁D1-E1	2423	34393.9	31472.5	83730	18901.7	1424.8	-0.4	0.5	176
D4◁D8	2780	34369.4	30025.0	105266	22584.3	1678.7	0.2	0.9	181
D8◁D4	2643	34059.8	29786.0	108050	22571.4	1673.1	0.3	0.9	182
D4◁D5	3924	33667.0	28655.0	90829	21639.2	1710.7	-0.2	0.8	160
D6◁D3	3723	33236.2	31951.0	77738	16076.6	1283.1	-0.6	0.4	157
D3◁D6	4241	32680.2	31692.0	75236	15758.4	1253.7	-0.7	0.4	158
D6◁D4	2626	32641.3	29603.0	89337	18647.6	1507.6	0.0	0.7	153
D4◁D6	4855	32596.8	30040.5	86278	17974.8	1477.5	-0.1	0.7	148
D5◁D4	2759	32481.7	27607.5	93882	22320.8	1682.5	-0.1	0.8	176
D5◁D3	2622	32156.4	28100.5	97347	20758.8	1547.3	0.6	0.9	180
D8◁D2	2213	32139.3	30687.0	81048	16582.3	1588.3	0.1	0.6	109
D3◁D5	3238	31541.8	27668.0	98783	20486.7	1522.8	0.6	0.9	181
D6◁D2	9399	30994.6	29380.0	63915	13436.8	1385.9	-0.7	0.5	94
D7◁D8	1175	30822.7	25352.0	119576	21742.3	1724.3	2.0	1.3	159
D6◁D1-E1	3200	30598.6	29019.0	73895	14829.4	1187.3	-0.1	0.5	156
D6◁D1-E2	2712	30532.6	27484.0	77638	15284.5	1227.7	0.1	0.6	155
D5◁D1-E2	2212	29554.9	25288.0	85125	19329.9	1457.0	0.1	0.8	176
D5◁D1-E1	2080	29211.9	25512.0	84722	18729.9	1403.9	-0.1	0.7	178
D8◁D7	1912	28235.2	21943.5	110007	20619.9	1554.3	1.6	1.3	176
D5◁D2	3084	27976.5	25509.5	72681	15657.1	1492.8	-0.4	0.5	110
D7◁D6	3950	24197.2	23126.0	67287	13355.2	1171.3	0.6	0.8	130
D7◁D3	3630	23419.4	20326.0	75757	14126.4	1306.0	1.5	1.1	117
D7◁D4	1768	22901.8	18129.0	85535	16788.8	1418.9	2.6	1.6	140
D6◁D7	2735	22518.3	20458.0	69774	14055.1	1171.3	0.6	0.9	144
D7◁D1-E1	2797	22307.9	19730.0	70627	12729.1	1341.8	2.4	1.3	90
D7◁D1-E2	2279	21869.7	19776.0	69883	12746.1	1358.7	2.3	1.3	88
D7◁D5	2928	20410.5	16995.0	57308	12478.9	1229.6	0.1	0.8	103
D4◁D7	1681	20318.7	15366.0	83754	16334.3	1283.3	2.8	1.6	162
D3◁D7	1879	19954.7	16457.0	74819	13852.6	1112.7	1.9	1.3	155
D7◁D2	4096	19854.4	16755.5	52781	10700.2	1405.0	1.0	1.1	58
D5◁D7	2147	17859.6	15216.0	56518	11992.7	1017.2	0.6	1.1	139

Legend:	D1: Contact, FTIR	D2: Contact, EL	D3: Contactless, Desktop	D4: Contactless Desktop	"◀": Contact Cases Only
	D5: Contactless Mobile Phone	D6: Contactless Mobile Phone	D7: Contactless Mobile Phone	D8: Contactless Mobile Phone	"◁": Contactless Cases

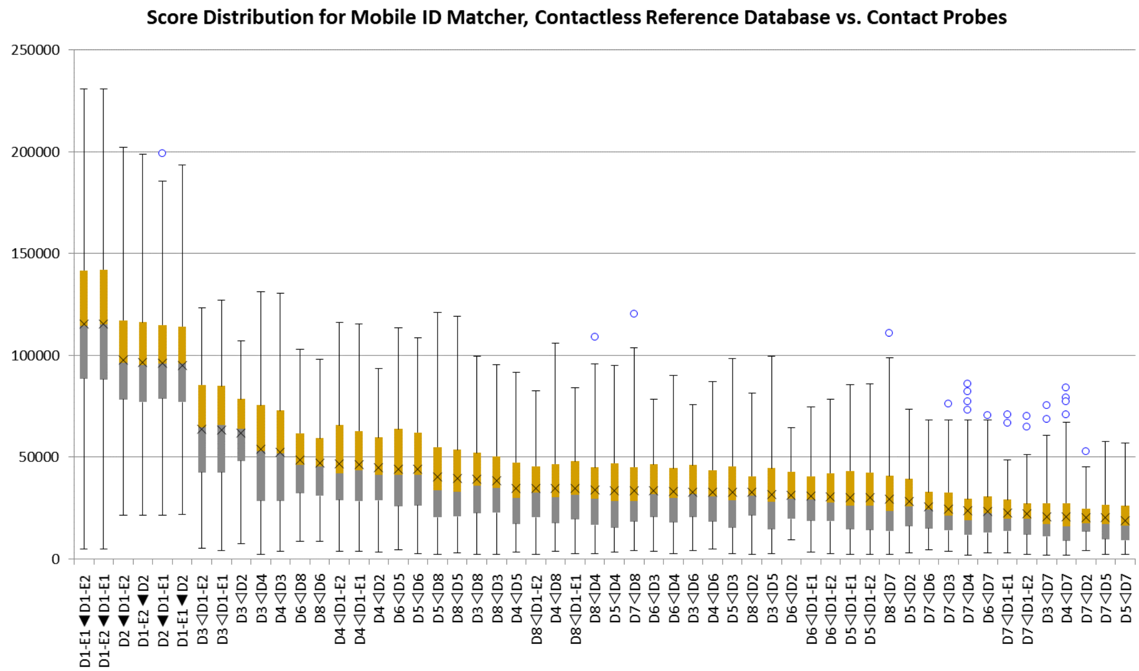

Figure 11: Boxplots Showing Score Distribution for Mobile ID Matcher, Contactless Reference Database vs. Contact Probes.

Table 15: Score Distribution Summary Statistics for Mobile ID Matcher, Contactless Reference Database vs. Contact Probes.

	Minimum	Mean	Median	Maximum	Standard Deviation	Standard Error	Kurtosis	Skewness	Count
D1-E1◀D1-E2	4733	115400.0	114494.0	231002	39928.7	2874.1	-0.2	0.0	193
D1-E2◀D1-E1	4909	115308.4	115136.0	231009	39784.9	2863.8	-0.2	0.0	193
D2◀D1-E2	21436	97754.0	96466.5	202155	32952.2	3033.5	0.3	0.2	118
D1-E2◀D2	21522	96499.4	95156.0	198978	32440.4	2986.4	0.3	0.2	118
D2◀D1-E1	21328	96131.2	96156.0	199143	31444.7	2894.7	0.7	0.3	118
D1-E1◀D2	21864	94977.0	95975.5	193724	30848.0	2839.8	0.5	0.2	118
D3◁D1-E2	5100	63865.7	64682.0	123374	28270.4	2050.9	-0.8	-0.1	190
D3◁D1-E1	4045	63478.3	65816.5	127236	28340.4	2056.0	-0.7	-0.1	190
D3◁D2	7515	61787.6	63971.0	107178	23952.7	2205.0	-0.7	-0.2	118
D3◁D4	2422	53948.6	53084.0	131157	29995.5	2187.6	-0.7	0.3	188
D4◁D3	3578	52393.9	51983.5	130487	29033.1	2128.8	-0.6	0.3	186
D6◁D8	8728	48593.7	46190.0	103023	21895.5	1741.9	-0.3	0.5	158
D8◁D6	8785	46981.6	45541.0	98134	21206.1	1687.1	-0.3	0.5	158
D4◁D1-E2	3602	46807.2	41962.0	116095	25076.9	1901.1	-0.5	0.5	174
D4◁D1-E1	3695	46482.6	43658.5	115638	24710.0	1873.3	-0.5	0.4	174
D4◁D2	3350	44767.4	41141.0	93599	21784.2	2167.6	-0.7	0.3	101
D6◁D5	4374	44199.6	41172.0	113523	23095.4	1873.3	-0.5	0.5	152
D5◁D6	2611	44161.6	41408.0	108642	22834.3	1852.1	-0.5	0.4	152
D5◁D8	2099	40314.8	33639.0	121148	26654.6	1938.8	0.0	0.8	189
D8◁D5	3125	39668.5	32981.5	119267	25888.1	1919.0	0.0	0.8	182
D3◁D8	2403	39179.2	36138.0	99787	22307.4	1622.6	-0.2	0.6	189
D8◁D3	2291	38383.0	35026.0	95275	21454.7	1577.4	-0.2	0.5	185
D4◁D5	3266	34837.8	29854.0	91867	22053.0	1782.9	-0.3	0.7	153
D8◁D1-E2	2313	34666.1	32623.0	82464	18828.3	1423.3	-0.2	0.6	175
D4◁D8	3699	34656.7	30432.0	106138	22784.9	1693.6	0.2	0.9	181
D8◁D1-E1	2437	34582.9	31501.0	84062	19182.0	1450.0	-0.5	0.5	175
D8◁D4	2647	34018.0	29696.5	108903	22865.5	1685.7	0.3	0.9	184
D5◁D4	3468	33645.7	28355.0	94980	22569.0	1741.2	-0.2	0.8	168
D7◁D8	4000	33629.1	28653.0	120375	21880.4	1842.7	1.8	1.3	141
D6◁D3	3739	33556.7	32004.0	78555	16244.8	1296.5	-0.6	0.4	157
D6◁D4	2643	33147.7	29982.5	90047	18762.4	1521.8	0.0	0.7	152
D3◁D6	4257	32975.3	31929.5	75938	15924.5	1266.9	-0.7	0.4	158
D4◁D6	4866	32951.3	30553.5	86963	18156.6	1492.5	-0.1	0.7	148
D5◁D3	2626	32774.3	28814.5	98342	20953.7	1570.5	0.6	0.9	178
D8◁D2	2312	32704.7	30932.5	81448	16432.9	1581.3	0.1	0.6	108
D3◁D5	2460	31712.4	27985.0	99533	20779.6	1540.3	0.6	0.9	182
D6◁D2	9445	31210.8	29480.5	64549	13536.6	1396.2	-0.6	0.5	94
D6◁D1-E1	3218	30840.4	29274.5	74580	14953.9	1197.3	-0.1	0.5	156
D6◁D1-E2	2728	30626.1	27591.0	78433	15491.3	1240.3	0.1	0.6	156
D5◁D1-E1	2242	30163.2	26254.0	85723	18750.9	1425.6	-0.1	0.7	173
D5◁D1-E2	2214	30033.0	26043.0	86157	19564.6	1483.2	0.1	0.8	174
D8◁D7	2108	29423.4	23748.0	110746	20908.1	1617.9	1.5	1.2	167
D5◁D2	3101	28333.3	25795.0	73622	15821.3	1515.4	-0.5	0.5	109
D7◁D6	4426	25703.7	24491.0	68291	13457.9	1238.9	0.5	0.7	118
D7◁D3	3658	24398.9	21264.0	76214	14521.0	1397.3	1.2	1.0	108
D7◁D4	1775	23710.4	18859.0	86033	17291.4	1510.8	2.2	1.5	131
D6◁D7	2934	23352.4	22524.0	70718	14142.5	1199.6	0.6	0.8	139
D7◁D1-E1	2810	22560.4	19961.0	70990	13191.7	1448.0	2.2	1.2	83
D7◁D1-E2	2293	22066.2	19946.5	70227	13090.3	1463.5	2.3	1.3	80
D3◁D7	1935	20913.8	17206.0	75282	14043.9	1166.3	1.7	1.3	145
D4◁D7	1749	20842.0	15931.0	84311	16576.0	1318.7	2.6	1.6	158
D7◁D2	4124	20456.8	17670.5	52930	11028.6	1559.7	0.8	1.0	50
D7◁D5	2240	20239.9	17302.0	57583	13365.3	1475.9	0.1	0.8	82
D5◁D7	2162	18998.2	16526.0	56938	12518.0	1138.0	0.3	1.0	121

Legend:	D1: Contact, FTIR	D2: Contact, EL	D3: Contactless, Desktop	D4: Contactless Desktop	"◀": Contact Cases Only
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